AD626477

FINAL REPORT

HIGH EFFICIENCY COOLING AND FACILITY MAINTENANCE (U)

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December 1965

Advanced Research Projects Agency
Department of Defense
Project DEFENDER
Washington, D. C.

and

Rome Air Development Center
Research and Technology Division
Air Force Systems Command
United States Air Force
Griffiss Air Force Base, New York

Project: 8794

Program Structure 920F, ARPA Order Number 388, Amendment #1.

(Prepared under Contract No. AF30(602)-3441 by Raytheon Company, Microwave and Power Tube Division, Spencer Laboratory, Burlington, Massachusetts.)

FOREWORD

The investigation of the High Efficiency Cooling and Facility Maintenance was carried out in the Super Power Operation of the Raytheon Microwave and Power Tube Division. This work was under the general direction of Mr. W. C. Brown, Manager, Super Power Operation. Mr. L. J. Nichols was the project engineer for the Diode Life Test Program and Mr. R. A. Peterson was the project engineer for the Facility Maintenance Program. Mr. Peterson is assisted by Mr. R. H. Edgar.

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ABSTRACT

An investigation of high efficiency Amplitron vane cooling was initiated in 1964 by Raytheon under the sponsorship of ARPA. This investigation was both theoretical and experimental. It included the following areas:

a. minimum burnout flux
b. effect of time on burnout flux
c. selection of optimum materials
d. effect of electron bombardment upon the vane material and the vane cooling capacity
e. erosion effects due to transient heating during a pulse
f. construction techniques to eliminate microleaks.

The previous super power Amplitron development program showed that CW power densities from 5 to 10 kW/cm^2 were feasible with a technique using high velocity coolant flow. The program discussed in this report showed peak power Amplitron vane capabilities of 250 kW/cm^2 at a 10 μsec pulse width.

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1.0 INTRODUCTION

During the super power CW program, the ability of the Amplitron to generate large amounts of CW power was demonstrated. As a result of the CW program, the ability of a pulsed Amplitron to generate large amounts of average power at nominal peak power levels and short pulse durations was virtually assured. What was not known, however, was whether or not the pulsed Amplitron could generate large amounts of average power at high peak power levels and long pulse durations.

High-duty-cycle pulsed operation of a tube produces average power vane heating which is comparable to the heating produced by CW power, but in addition there is a transient surface heating which is superimposed on the average power heating. Use of high velocity coolant flow through the tube vanes allows pulse tube operation at high average power but has little effect upon the transient surface heating. The ability of a pulsed tube to generate high peak power is dependent upon the characteristics of the material in a thin layer at the anode vane surface because the transient heating due to pulses measured in microseconds or tens of microseconds is concentrated in a thin layer at the vane surface.

In order to design Amplitrons capable of generating high peak power, the effect on materials of pulsed electron bombardment must be known. A program was sponsored by ARPA at Lincoln Laboratory under Air Force contract AF 19(628)-500 (ARPA Order 85) to obtain knowledge about the effects of electron bombardment on the surface temperature of a solid. As a result of this program, the means of determining the surface temperature of any solid under electron bombardment was available. This knowledge allows anode vane facings to be designed so that surface melting will not occur. However, many pulse tube anode vanes have failed under conditions where melting does not occur. These failures occurred due to fatigue caused by the transient thermal stress at or near the vane surface. In order to determine how well a material will resist surface cracking or crazing due to transient thermal stress, the material must be bombarded by electrons at different dissipation levels and over long periods of time.

A knowledge of how well materials resist this type of fatigue failure is essential for designing high peak power Amplitrons capable of operating for long periods of time. Because this knowledge was not available, ARPA sponsored the high efficiency Amplitron vane cooling program so that a life test program could be carried out to obtain this knowledge.

2.0 SUMMARY

The evaluation of pulsed peak power Amplitron vanes has been carried out in the following four programs.

The first program consisted of the design and evaluation of an inverted magnetron diode. During this program a test vehicle suitable for testing vanes at dissipation levels up to 400 kW/cm^2 was designed and evaluated.

The second program consisted of a study to determine the most suitable materials for pulse tube vanes, and the incorporation of these materials in test vanes. The six most suitable materials for pulse tube vanes were selected and the techniques for incorporating these materials in test vanes were worked out.

The third program that was carried out consisted of designing and constructing a diode life test facility which allowed a number of diode tests to be conducted simultaneously.

During the fourth program the effects of pulsed electron bombardment of platinum was studied. The effect was studied at five different dissipation density levels. This study confirms that surface stress cracking will occur at dissipation density levels over 100 kW/cm^2 at a 10 μsec pulse width. It shows that while there is a large amount of surface roughening at dissipation density levels of 250 kW/cm^2, thousands of hours of operation are possible at dissipation density levels up to 250 kW/cm^2. At dissipation density levels of 280 kW/cm^2, extensive surface diffusion was taking place. A vane tested at this level for 330 hours showed serious deterioration.

3.0 DIODE DESIGN AND EVALUATION

The development of the diode itself, involving principles that had not been tested out before, was a major undertaking and represented an important part of the program. The basic difficulty in building a suitable test diode for bombarding a single vane is the cathode. A diode without a magnetic field cannot be used because there is too great a requirement of the peak primary emission of the cathode for any reasonable life. If an attempt is made to use combinations of magnetic field and the secondary emitting properties of a thermionic cathode, then the high duty cycles involved in the testing result in the melting of the cathode by back bombardment. The only feasible test diode, therefore, must employ a water-cooled secondary emitting cathode which is capable of furnishing large amounts of emission while still being able to dissipate the back bombardment power. However, these cold cathode diodes are not self-starting, and it is necessary to start them in some manner. In this particular case, rf injection was used. These test diodes have performed their function. Because of the complexity of the diode, a considerable portion of the total effort represented by the contract was spent in first developing the diode and then building a quantity of them to be used in test.

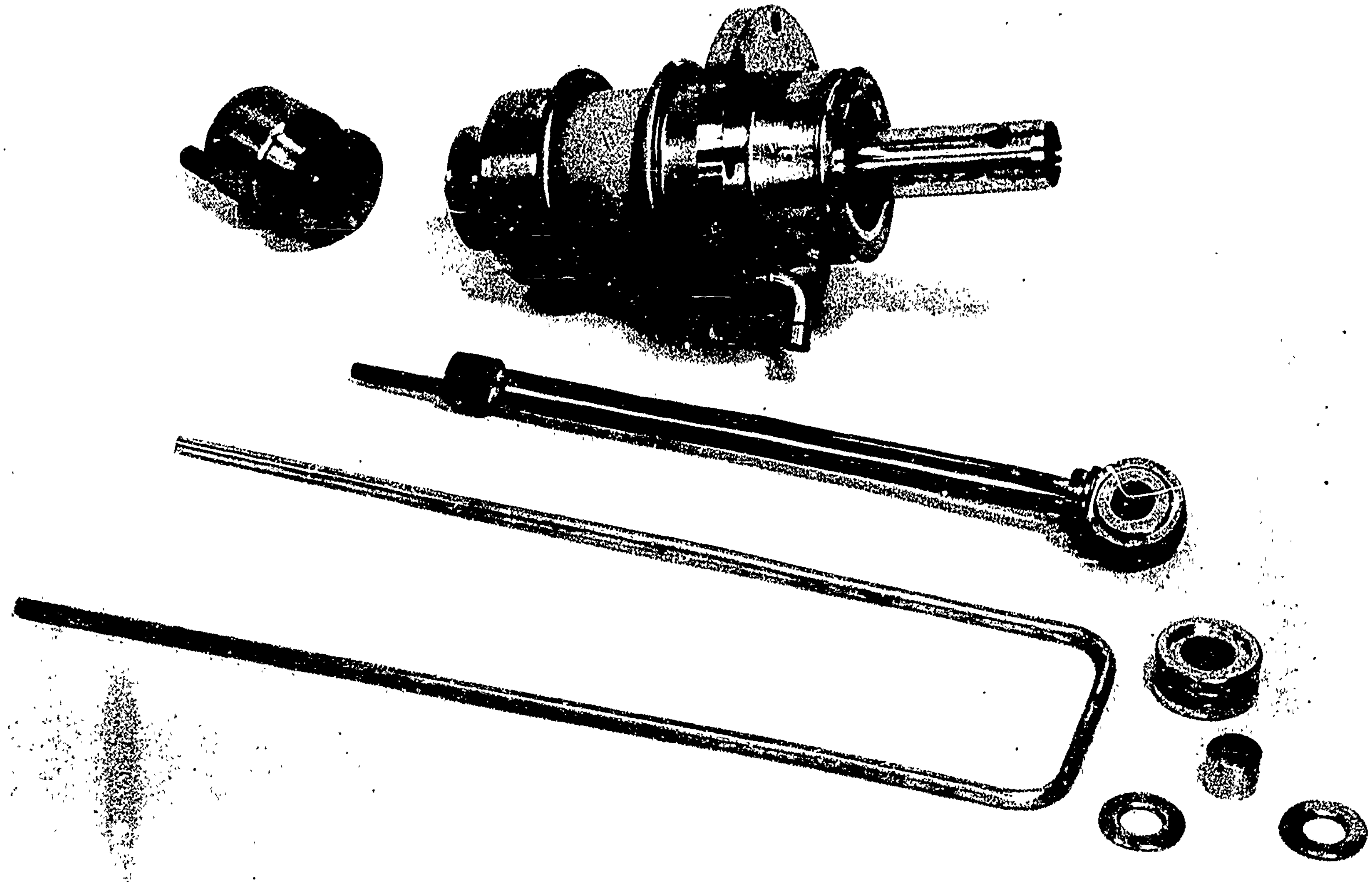
3.1 Diode Design

The test vehicle consists of a magnetic diode using a platinum cathode whose emission is stimulated by an rf signal. (Reference Figure 3.1.)

The vane test vehicle consists of a cylindrical diode having an inverted geometry with the cathode enclosing the anode as shown in Figures 3.2 and 3.3. The anode consists of a vane section constructed to be readily removable for cross-sectioning and microscopic analysis. The remainder of the structure is built with welded joints for simple disassembly and replacement of cathode and anode.

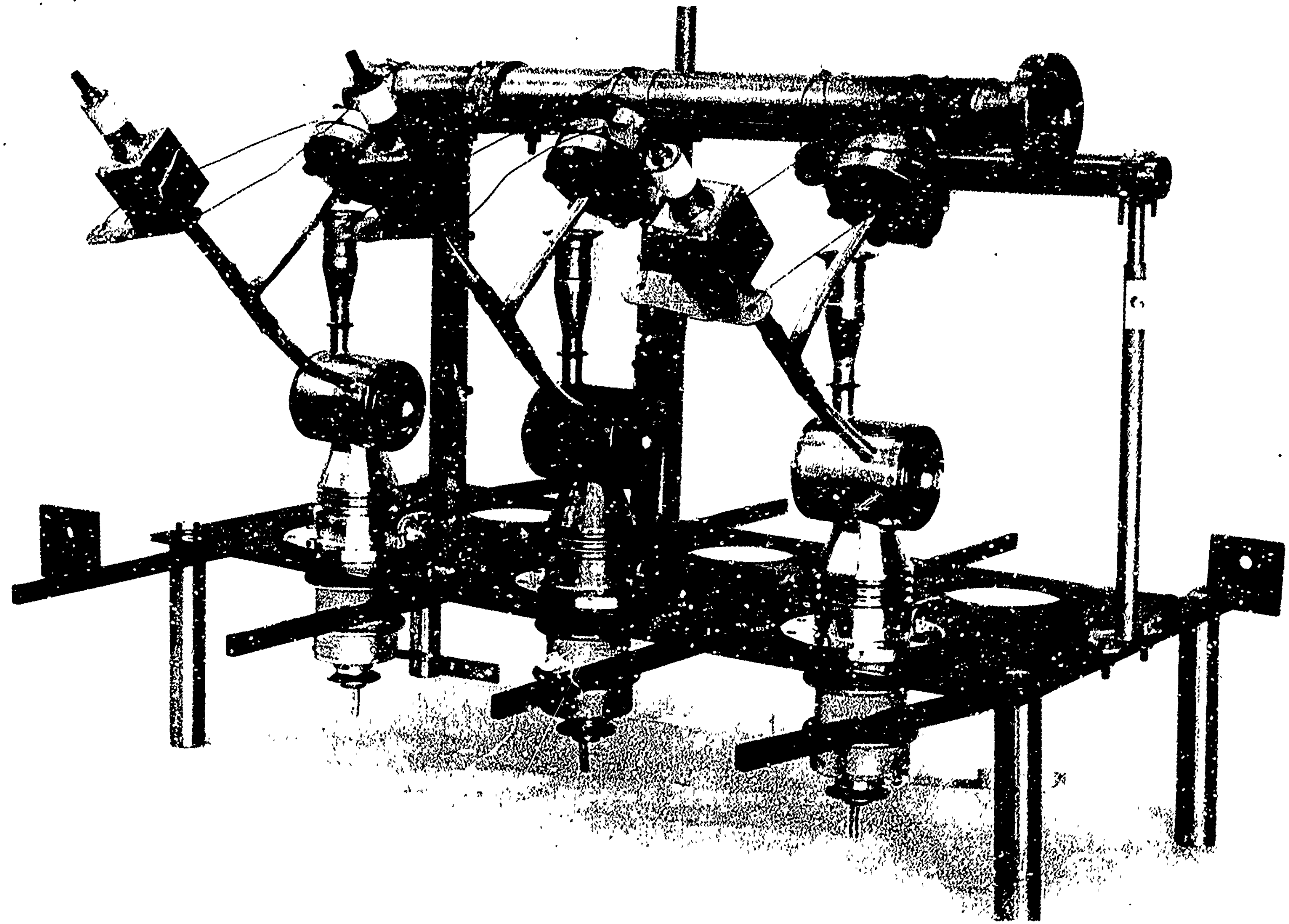
The primary consideration in the design of a test vehicle is the maximum power density required on the anode during test. The evaluations of materials

Figure 3.1



CATHODE ASSEMBLIES

Figure 3.2



TEST DIODES MOUNTED FOR BAKEOUT

Figure 3.1

suitable for pulse tube vane facings (reference Section 4.0, Material Selection) indicates that a power density of 600 kW/cm^2 at a pulse width of 10 µsec would be sufficient to test the major portion of the materials near their maximum level. No theoretical basis exists for the determination of anode-cathode dimensions and the resulting E-I characteristic for a magnetic diode. However, McNall[1] using cathodes of different secon ry emission ratio has arrived at an empirical relationship for the maximum current boundaries in a particular magnetron. This expression is,

$$I_a = 1.6 \times 10^{-6} (\delta - 1) \frac{h}{r_a} \frac{V_a^{3/2}}{\left[1 - \left(\frac{r_c}{r_a}\right)^2\right]^2 \left(\frac{r_a}{r_c} + 1\right)}$$

Using this expression and the maximum current boundary obtained by Jepson[2] with a platinum cathode, a secondary emission ratio of 5.2 is obtained.

Utilizing the anode-to-cathode ratio used by Jepson and an anode diameter the same as the pulse tube vane, the perveance of the diode can be obtained.

The expression relating anode current boundary per centimeter of length then becomes

$$I_a = 2.4 \times 10^{-6} V_a^{3/2}$$

Substituting the above diode parameters into the Hull cutoff expression

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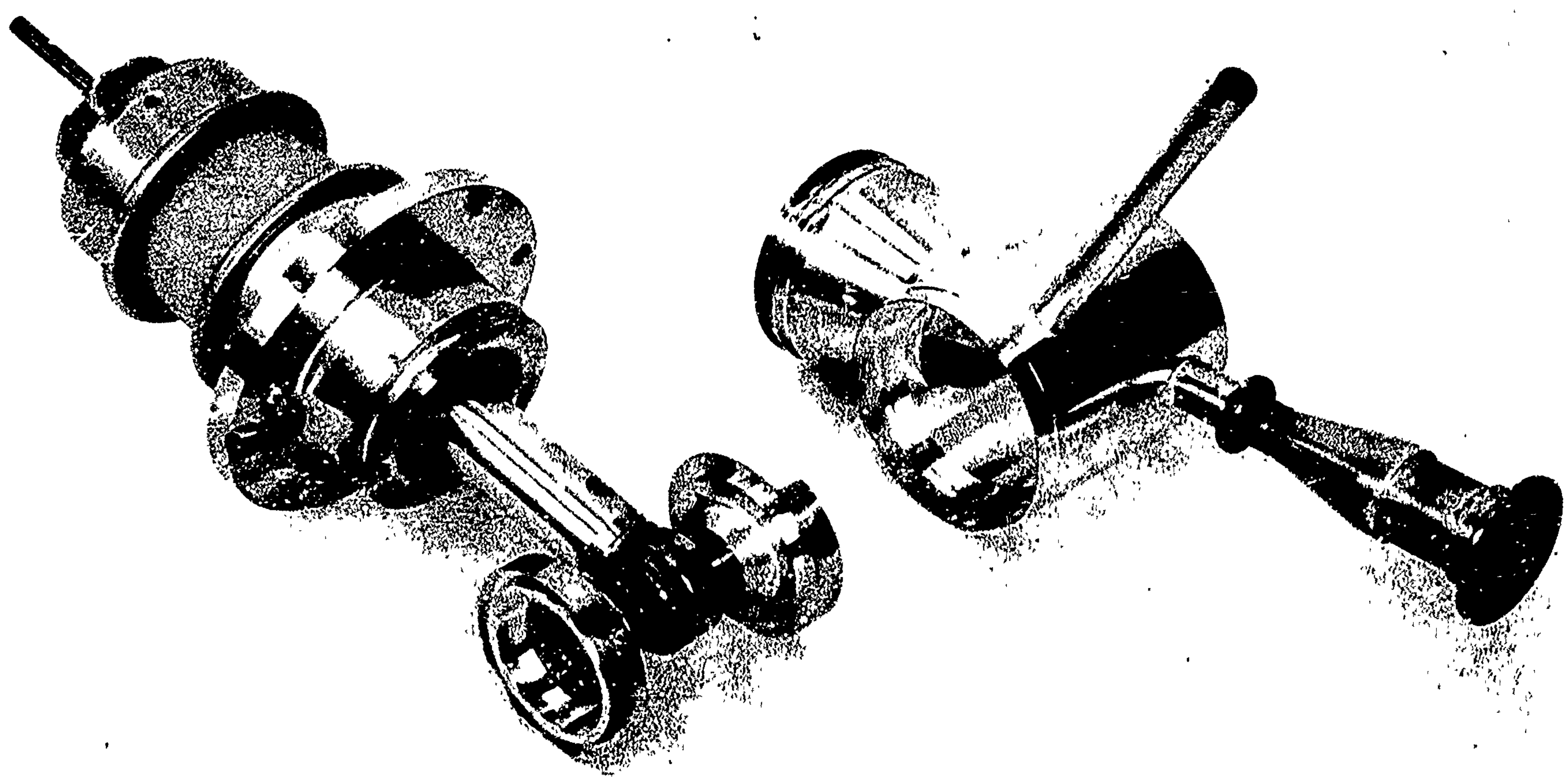
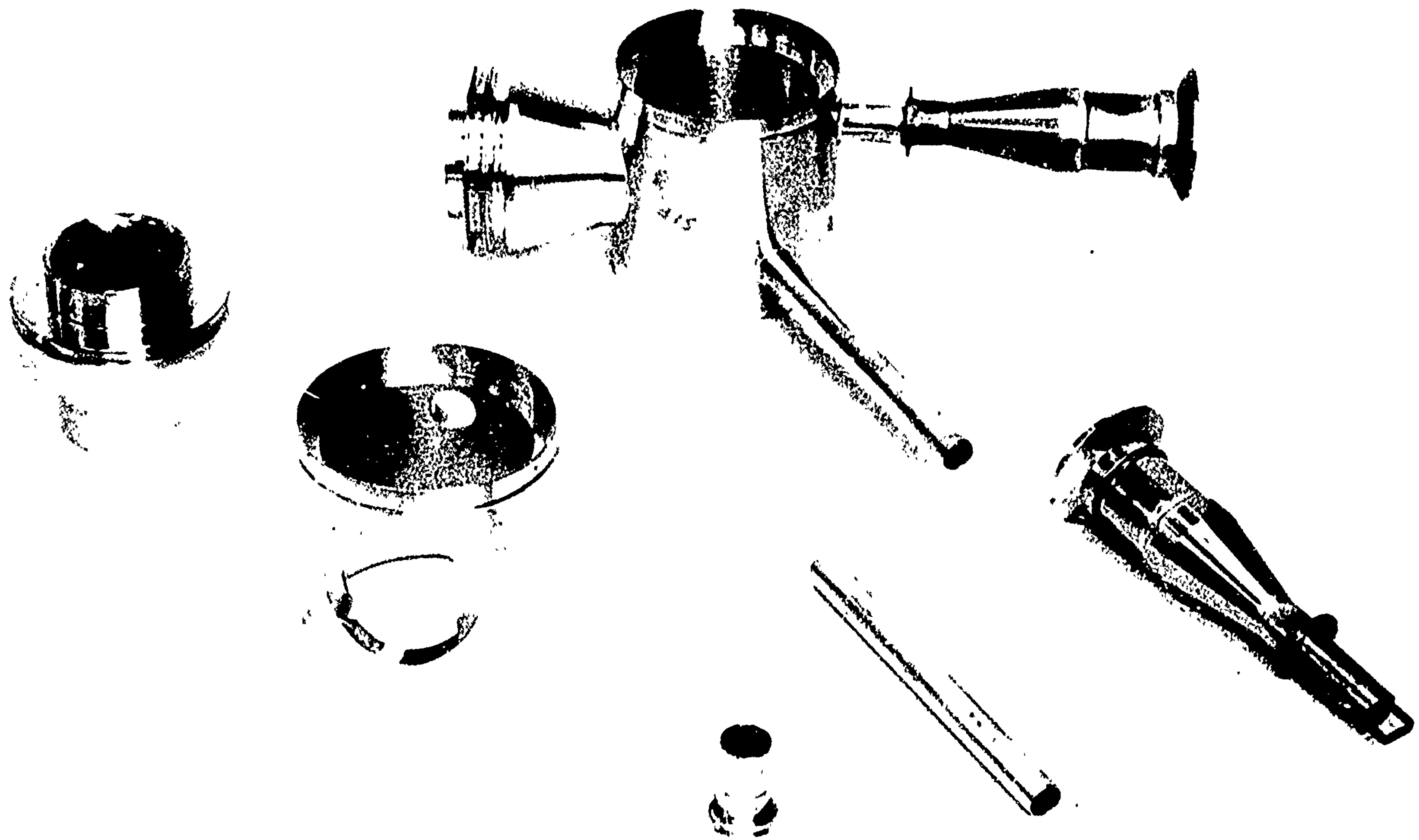
1. J.W. McNall, H. L. Steele, and C. L. Shackelford, Westinghouse Electric Co. Research Report Number BL-R-929-76-1.

2. R. L. Jepson and M. W. Muller, "Enhanced Emission from Magnetron Cathodes," J. of Appl. Physics, Vol. 22, No. 9, September 1951.



CATHODE-ANODE ASSEMBLY

Figure 3.3



RF COUPLER AND VACUUM CAVITY
Figure 3.4

for an inverted magnetron gives,

$$V_c = .0106\ B^2$$

The actual voltage at the maximum current boundary is reported in the literature[2, 3] as lying between $V_c/2$ and V_c. The maximum power dissipation per centimeter in the anode as a function of the magnetic field would be,

$$P_{max} = 2.4 \times 10^{-11}\ B^5$$

The minimum anode dissipation per centimeter would be

$$P_{min} = 4 \times 10^{-12}\ B^5.$$

This indicates that for a field strength of 2500 gauss, dissipation denisty at the vane facing would be between 170 kW/cm^2 and 960 kW/cm^2.

In order to excite emission, an rf signal is used. The rf signal is loop coupled into a coaxial cavity formed by the diode anode and the surrounding vacuum enclosure (reference Figure 3.4). The cathode is capacitive-coupled to the coaxial cavity and tunes it down in frequency. The loaded Q of the cavity is approximately 150, and the unloaded Q 300.

3.2 Diode Evaluation

Diode #1 was operated with a maximum magnetic field of 2000 gauss. The anode voltage was 40 kV at the upper current boundary and an anode dissipation of 242 kW/cm^2 was obtained. Tests on the initial diode were done with a 4 μsec pulse on the rf exciter and diode. To achieve the above level, the rf exciter was operated at its

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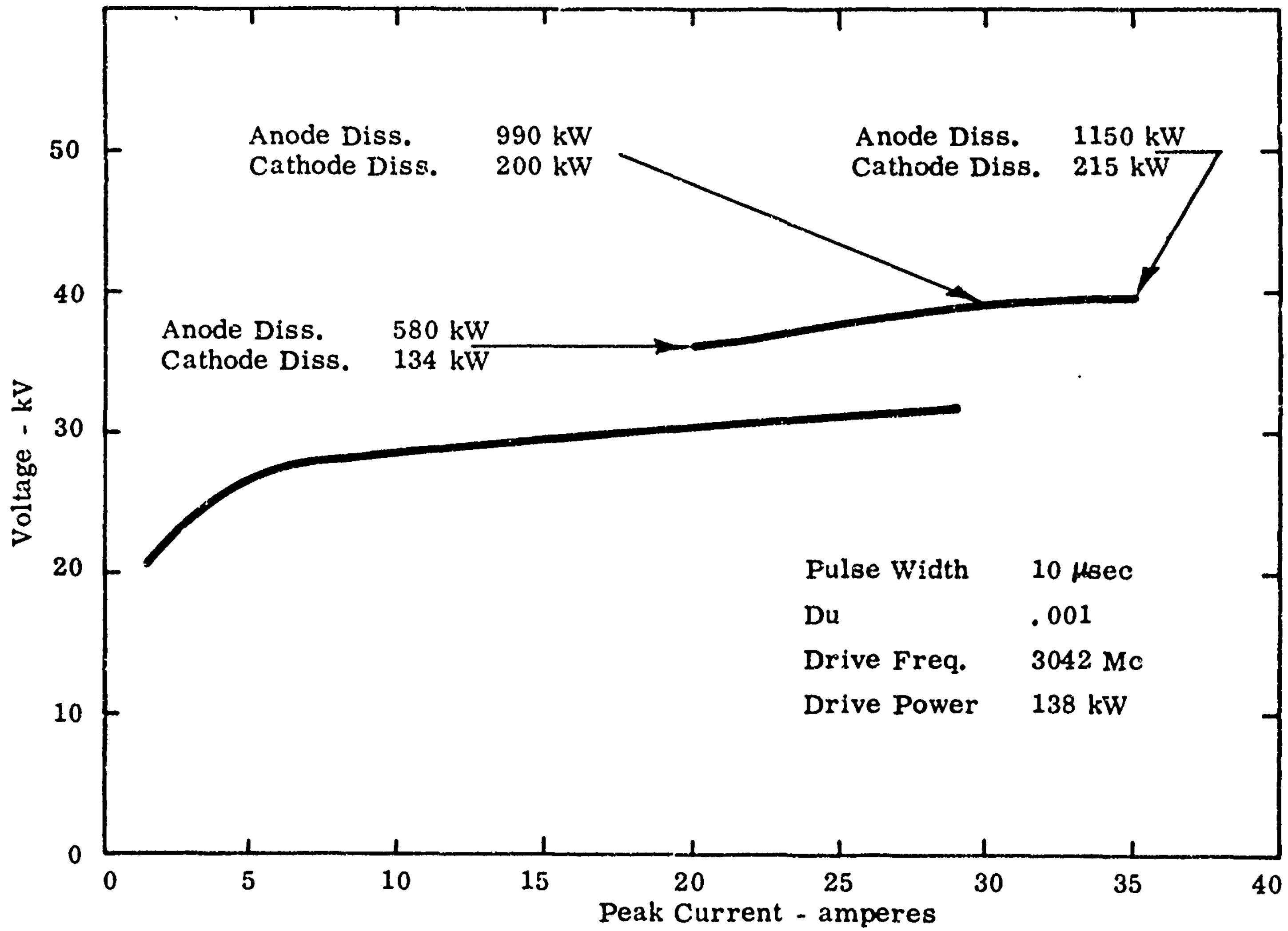
3. Fraenkel, Z., IRE Trans. PGED, July 1957, pp. 271-280.



MAGNETIC DIODE
E-I CURVE

Figure 3.5

lowest stable operating level (approximately 50 kW) and it was necessary to start the rf exciter approximately 4 μsec before the diode pulse. The rf pulse decreased to 10 to 20% of its maximum value before the start of the voltage pulse on the diode. As the diode was raised from its minimum current level (approximately 6 amperes at 30 kV) to its upper limit, it was necessary to readjust the alignment of the pulses by two to four tenths of a microsecond.

Diode #3 was constructed with internal pole pieces so that it was possible to operate at a magnetic field of 2500 gauss. This tube was tested with an eight μsec pulse on the rf exciter and a 10 μsec pulse on the diode. At an rf level of approximately 50 kW, with the rf exciter starting slightly less than a half a μsec before the diode pulse, the diode operated between one and seven amperes at 38 to 39.5 kV. With a drive power of 100 kW or better and the exciter starting slightly before the diode, the diode would run out on the lower curve shown in Figure 3.5. At 138 kW, the diode would operate out along the lower curve to 29 amperes and then jump into the upper mode at 20 amperes and 36 kV. There were occasions when the diode would not jump into this mode, but would jump from the lower to the upper mode on alternate pulses. When this occurred there were signs of instability in the rf exciter.

Diode #5 has a cathode-to-anode ratio which is 5% less than that of diode #3. With the rf exciter operating at a maximum of 80 kW, the predominant mode of operation of this diode was between 15 and 18 kV with a current maximum of 17 amps. On several occasions, the tube operated between 37 and 40 kV. However, stable operation at the higher voltage was not possible. An increase in drive power may have enabled the diode to operate stably in the higher mode, however, the rf exciter would not operate stably beyond the 80 kW level at the time that these tests were being carried on.

4.0 MATERIAL SELECTION

Suitability of a material for use as a pulse tube vane facing depends upon whether or not it can be incorporated into the tube with reasonable effort and upon the following characteristics of the material:

1. vapor pressure at elevated temperature
2. heat conductivity
3. volume specific heat
4. strength of the material vs. temperature
5. coefficient of expansion
6. modulus of elasticity
7. melting point of the material
8. secondary emission ratio.

Ahern's report[4] shows a listing of materials with two figures of merit. One is the product of thermal conductivity by tensile strength at room temperature, the other is the product of thermal conductivity by melting point. The eight materials with the highest figures of merit are tungsten, molybdenum, titanium, copper, silver, rhodium, pure nickel, and gold. Dispersion hardened copper rates high according to these two figures of merit. Because the secondary emission ratio of the material is important, consideration of platinum, rhodium, ismium, iridium, and rhenium is indicated.

An initial screening of materials leaves us with thirteen materials for consideration. These materials are listed in two groups. One group lists materials which would be difficult to incorporate into the tube, the other group represents materials that can be readily incorporated into a tube.

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4. Technical Note #9, "Ultra High Power Amplitron," Air Force Contract No. AF30(602)-2205.

Difficult to Incorporate Into the Tube	Readily Incorporated Into the Tube
titanium	tungsten
osmium	molybdenum
	copper
	silver
	rhodium
	pure nickel
	gold
	dispersion hadened copper
	platinum
	rhenium
	iridium

As indicated in Ahern's report, titanium has advantages over the other metals investigated. Its strength at high temperature, thermal conductivity, high melting point and corrosion resistance indicate that it may be feasible to use a vane of this material. The reason that this material is difficult to incorporate into the tube is that titanium has a phase transformation at 885°C, and distortion occurs. There is also a copper-titanium eutectic formed at 900°C. A tube with titanium vanes would have to be brazed with low temperature solders in a very dry inert atmosphere. This means that oxidized steel jigs could not be used to assemble the tube. These difficulties can be overcome; however, titanium's low secondary emission ratio weighs heavily against trying to overcome these difficulties.

The secondary emission ratio of a vane material is important because during high voltage aging of two electrodes in a vacuum there can be a transport of material from the anode to the cathode. Materials with low secondary emission ratio such as titanium would poison the cathode. If the amount of material transferred is small, the electrons and ions bombarding the cathode may perform a cleaning action and hence keep the emission from deteriorating.

Osmium has a high melting point and a low vapor pressure at elevated temperatures and a high secondary emission ratio. Its thermal conductivity is close to that of platinum. The reason that osmium is difficult to incorporate into the tube is that it is completely unworkable and can only be formed by powder metallurgy techniques.

Both these materials (titanium and osmium) have advantages as possible vane materials, but they present severe construction problems.

Of the materials which can be readily incorporated into the tube, tungsten, molydbenum, copper, dispersion hardened copper, platinum, rhodium, rhenium, and iridium have been selected as the materials that it would be most profitable to consider.

Nickel has been eliminated because its magnetic properties make it unusable in the interaction area at temperatures below its Curie point. Silver is not being considered because of its high vapor pressure at elevated temperatures. Gold is not being considered because of its low creep strength at elevated temperatures.

This group of materials has been considered for evaluation as pulse tube vane facing material because they can be readily incorporated into a tube and because they have characteristics which make them suitable for this use.

Pulse tube vanes are subjected to high temperature transient heating due to electron bombardment during the pulse. This heating is primarily a surface phenomena with the temperature into the vane material decreasing rapidly. The temperature rise of the vane surface for a given pulse width is inversely proportional to the square root of the thermal conductivity times the volume specific heat of the vane facing material. Formation of a figure of merit which is the product of the temperature at which a material has a vapor pressure of 10^{-8} Torr times its thermal conductivity and volume specific heat will allow a comparison of the above material for use as vane facing material. The materials are listed with their figure of merit normalized to that of platinum.

Material	Figure of Merit
copper	3.7
tungsten	3.4
iridium	2.4
rhodium	2.2
molydbenum	1.7
platinum	1
rhenium	1

The above listing indicates that copper is the first choice for pulse vane facings. However, the low secondary emission ratio of copper (less than one at 2 kV) means that a buildup of this material on the cathode will severely limit the emission of the cathode. Operating a copper vane at a 1% duty cycle and at a temperature such that the vapor pressure is 10^{-8} Torr, 500 hours would be required to coat the cathode with a molecular layer of copper if all of the copper evaporated from the anode deposited on the cathode. Unless electrons and ions bombarding the cathode can remove the copper at a more rapid rate than it is being deposited, then tubes using copper vane facings must be operated at a lower temperature than the above figure of merit indicates for long life.

The same limitation exists for tungsten and molybdenum. However, iridium, rhodium, platinum, and rhenium all have high secondary emission ratios and should not poison the cathode.

If the peak power Amplitron is operated at a .007 duty cycle, the average temperature rise in the vanes will be approximately 200°C. This indicates that the allowable temperature rise due to transient heating during the pulse for each of the vane facing materials is:

Material	Allowable Temperature Rise
copper	530°C
tungsten	1870°C
iridium	1250°C
rhodium	1080°C
molybdenum	1380°C
platinum	1090°C
rhenium	1730°C

Taking the above allowable temperatures into account plus the material's specific heat and conductivity, tungsten appears superior to all of the other materials for vane facing material.

Utilizing the calculations of Vibrans' group at Lincoln Laboratory[5] curves have been plotted of surface temperature rise versus pulse width with dissipation density as a parameter. These curves for each of the above listed vane facing materials are shown in Figures 4.1 and 4.2.

These curves show that tungsten, copper, molybdenum, and rhenium should be capable of 500 kW/cm^2 of dissipation at a pulse width of 10 μsec. Only tungsten appears satisfactory at a dissipation level of 1 mw/cm^2 and 10 μsec pulse width.

A factor which has not been considered in the previous discussion is thermal fatigue. Tube failures have been reported due to fatigue caused by the stress produced by pulse of heat flow. Crapuchettes[6] has described this phenomenon and has

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5. G. E. Vibrans, "Calculation of the Surface Temperature of a Solid Under Electron Bombardment," Lincoln Laboratory Tech. Report No. 268, November 16, 1962.

6. P. W. Crapuchettes, "Cooling of Anodes Subjected to Long Pulses of High Peak Power," AIEE Conference Paper, AIEE Winter General Meeting, New York, (29 January to 3 February 1961).

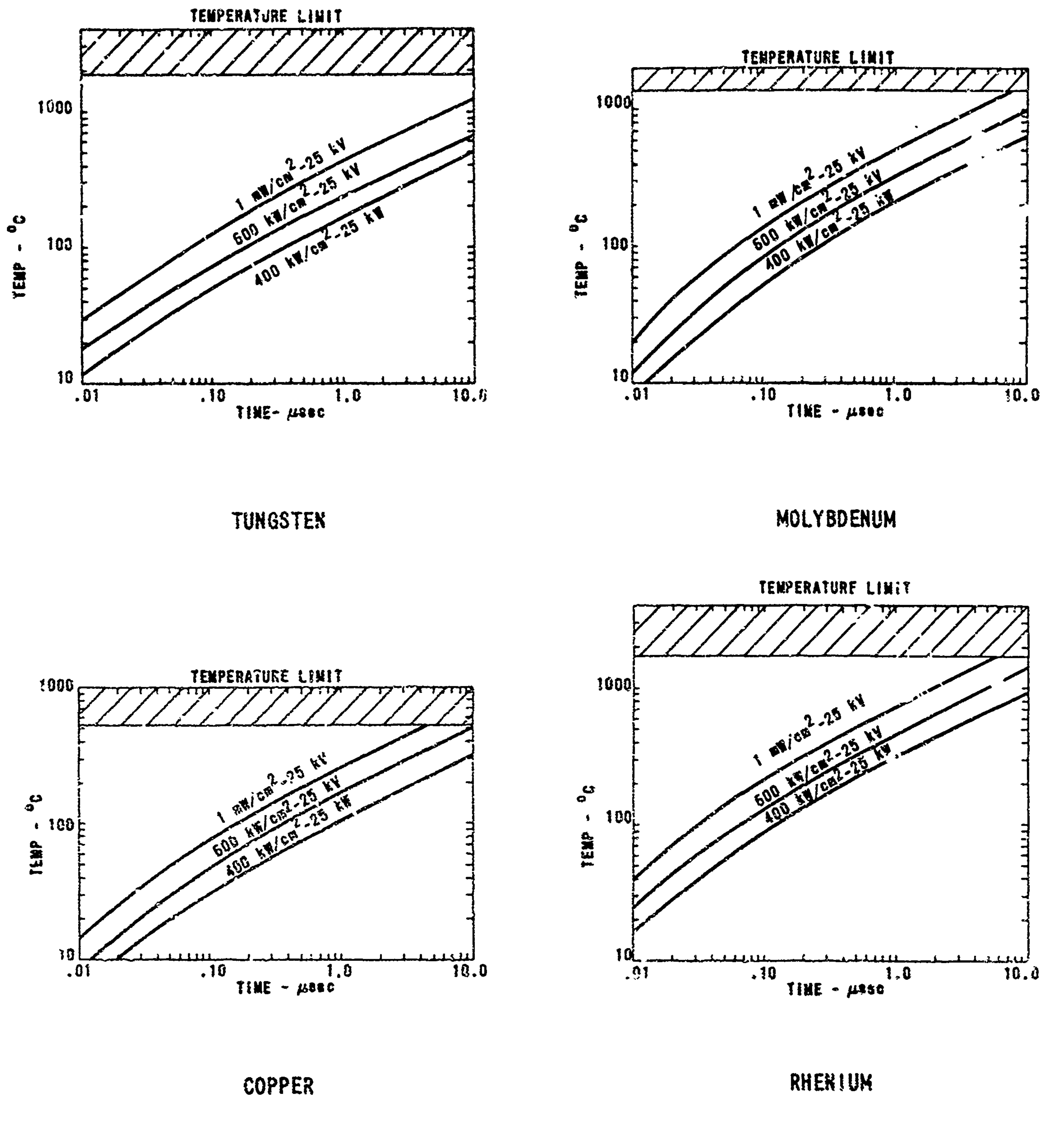
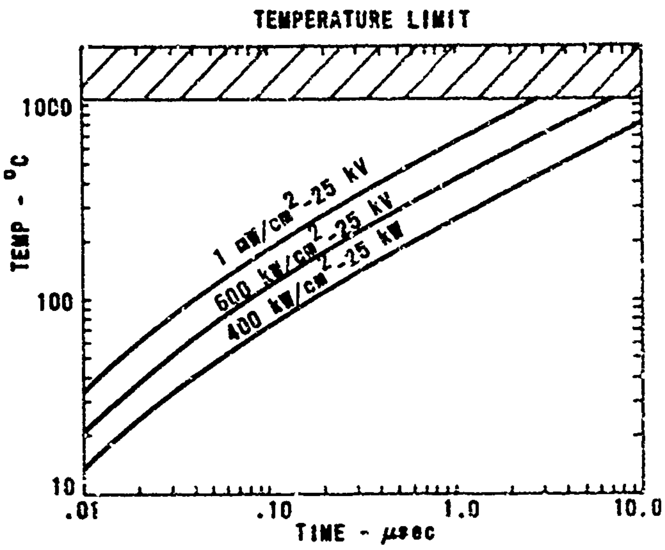
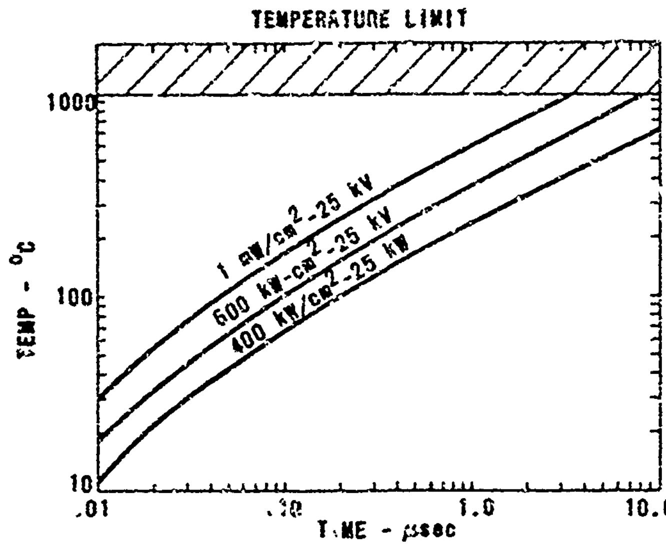


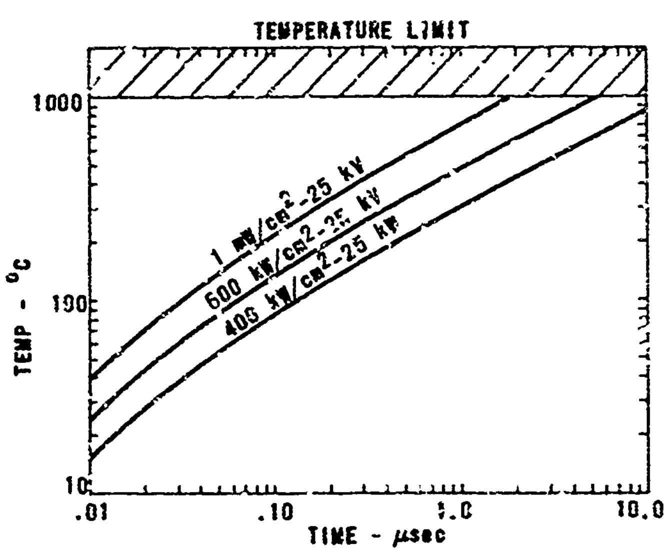
FIGURE 4.1 SURFACE TEMPERATURE vs PULSE WIDTH



PLATINUM



RHODIUM



IRIDIUM

FIGURE 4.2 SURFACE TEMPERATURE vs PULSE WIDTH shown how it is a function of the temperature variation and the average temperature. His calculations show that a transient temperature rise of less than 40°C will cause stress cracking in the average temperature range of 0 to 500°C in copper.

His expression for the allowable temperature rise at a given average temperature is a function of the fibre stress at yield point, modulus of elasticity, and thermal expansion.

$$\Delta T \;\alpha\; \frac{s}{bE}$$

s - fibre stress at yield point
E - modulus of elasticity
b - thermal expansion

For the materials being considered, the factor s/bE normalized to copper is as follows:

Material	s/bE
tungsten	19
copper	1
iridium	6.3
rhodium	32
molybdenum	9
platinum	.9
rhenium	.9

The above factors were calculated for approximately 100°. In order to determine the stress limits for different materials, it is necessary to determine the above characteristics versus temperature. It was not possible to collect sufficient data to do this. The above normalized factor gives a qualitative indication of the ability of these materials to resist thermal fatigue.

The characteristics of rhenium indicate that it will have a resistance to thermal fatigue comparable to copper at low temperatures. At elevated temperatures, this material maintains its strength and is one of the strongest known metals.

5.0 DIODE TEST FACILITY

5.1 Description

In pursuance of the objectives of the peak power pulsed diode life test program, a test facility has been designed and constructed. An important feature of this facility allows rapid accumulation of data by permitting the simultaneous testing of a number of diodes.

The system consists of the following basic items:

1. An oil tank which serves as a support for the tube and provides a means of access to the high voltage.

2. A low pressure cooling manifold (an extension of the existing low pressure high purity cooling system) supplies cooling water to the cathode at a pressure of 60 lb/in^2 and a flow of 1 gal/min/diode. The water flow-through and temperature differential across the cathodes is monitored.

3. A high pressure cooling manifold (an extension of the existing high pressure cooling system) supplies cooling water to the anodes so that a flow of 3 gal/min/diode at a pressure of 200 lb/in^2 can be obtained. The water flow-through and temperature differential across the anodes is monitored.

4. An rf feed system is required to trigger secondary emission in the diodes. The source of rf power is the existing QK622 driver chain.

5. A remote console located in the control room receives all data inputs (reference Figure 5.1). The following inputs are received:

Cathode	-	temperature differential
Anode	-	temperature differential
Anode	-	water flow
Diode	-	gas pressure
Diode	-	average current
Diode	-	peak current viewing.

It should be noted that wherever possible the total instrumentation requirements have been kept to a minimum by the extensive use of switching and by the use of existing facilities.

For example, all temperature differential inputs are fed to an existing T.D. readout system located in the super power pulse tube control console. New Instrumentation was not required for anode flow measurements because the turbine flow meters in the existing pulse tube cooling system were incorporated into the diode cooling system. In general, only one input may be viewed at a time.

6.0 DIODE LIFE TEST

6.1 Diode Life Test Summary

The following chart gives a summary of the diode life testing.

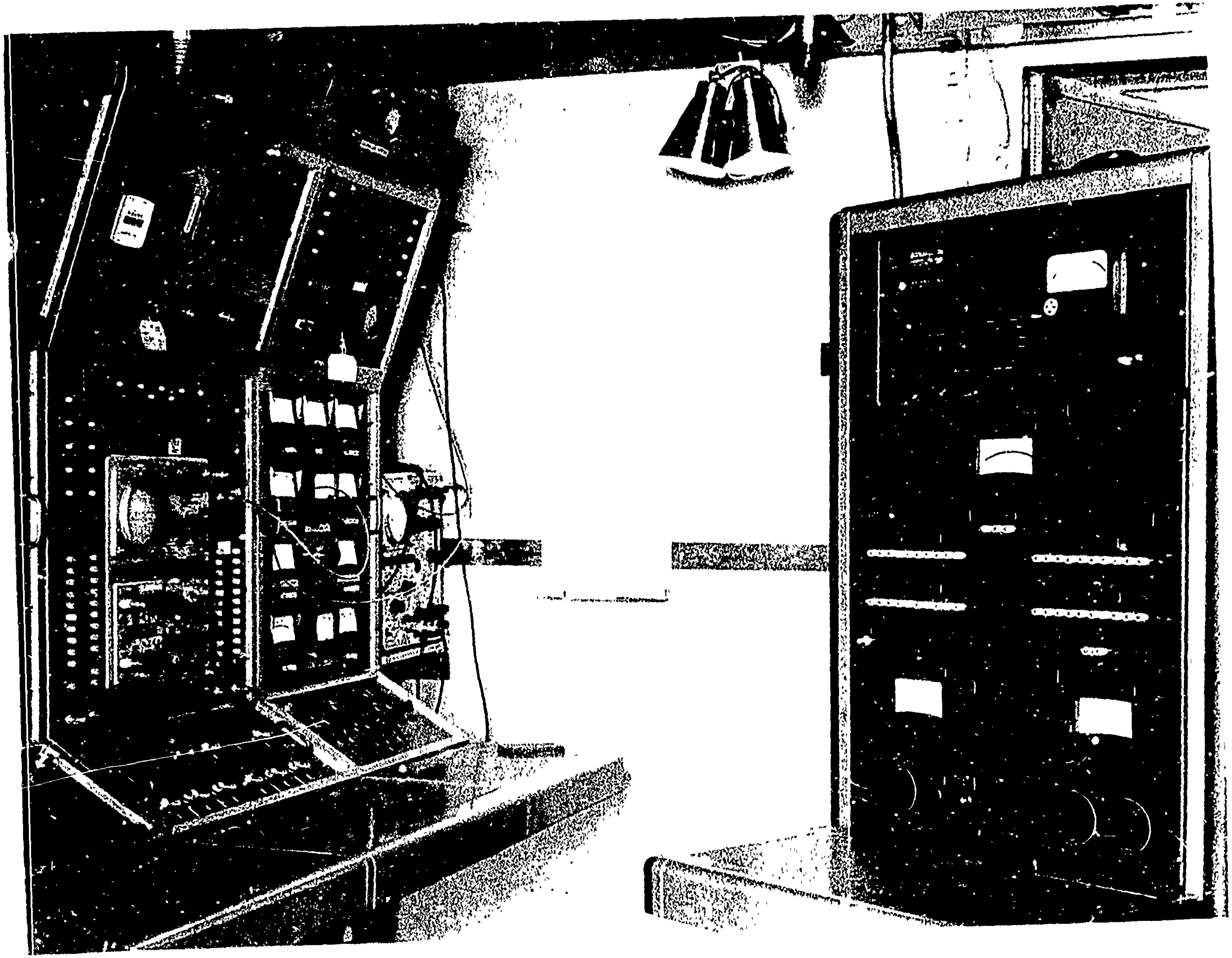
Diode #	Dissipation Density	Operating Time (hrs)	
3	280 kW/cm^2	330	
6	250 kW/cm^2	275	
1	148 kW/cm^2	110	
4A	12 kW/cm^2	24	X
5	96 kW/cm^2	17	X
4	96 kW/cm^2	20	X
7	--	--	

Total Operating Time - 420 hours

X - rf coupler failed.

Figure 5.1

Diode life testing was carried out by connecting five diodes in parallel on the life test rack. The total operating time of the system was 420 hours. However, it was not possible to operate all of the diodes simultaneously. The primary reason for this is that it was not possible to drive the diodes with enough rf for simultaneous operation without breakdown in the rf coupler. During the main portion of the operating time, the diodes were operated at a PRR of 200 pps. However, there were short periods of time when driver instability necessitated operation at PRF's of 300 and 400 pps.



DIODE LIFE TEST CONSOLE

Figure 5.1

6.2 Evaluation of Diode #4 and Vane #20

6.2.1 Description of Diode #4 and Vane #20

Diode #4 consisted of an inverted magnetron diode with a platinum cathode and a platinum-clad anode. The anode is vane #20. The dimensions of this vane are as follows:

outer diameter	.311"
inner diameter	.125"
total length	2.375"
length of interaction area	.400"
platinum vane cladding	.005"

Electron emission is obtained by exciting secondary electrons with rf.

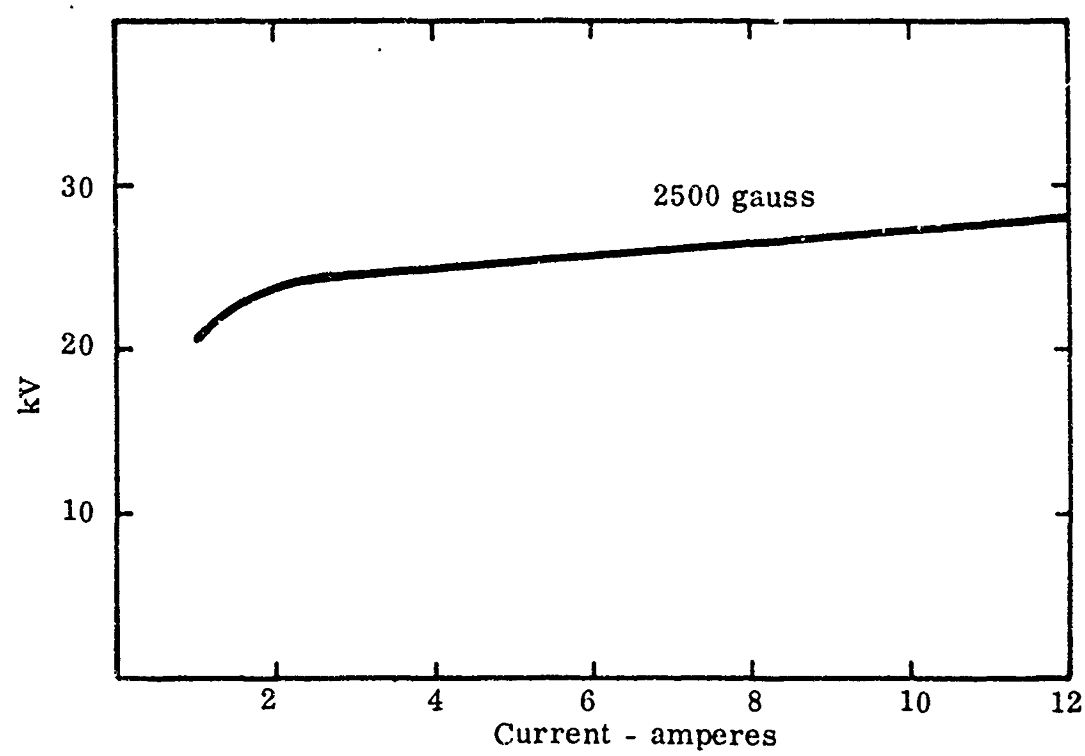
This diode was initially tested under the following conditions:

pulse width	4 μsec
repetition rate	100 pps
magnetic field	2500 gauss
rf starter signal	80 kW at 3042 Mcs.

The initial test data taken on this diode are shown in Figure 6.1. The cutoff voltage for this gauss level is 63 kV.

6.2.2 Life Test Operation

Diode #4 was life tested under the following conditions:



MAGNETRON DIODE #4

E-I CURVE

Figure 6.1

anode dissipation density	96 kW/cm^2
cathode dissipation density	15 kW/cm^2
pulse width	10 μsec
repetition rate	200 pps
total operating time	20 hours
total number of pulses	14×10^6

Operation at the above anode and cathode dissipation densities produced the following temperature gradients:

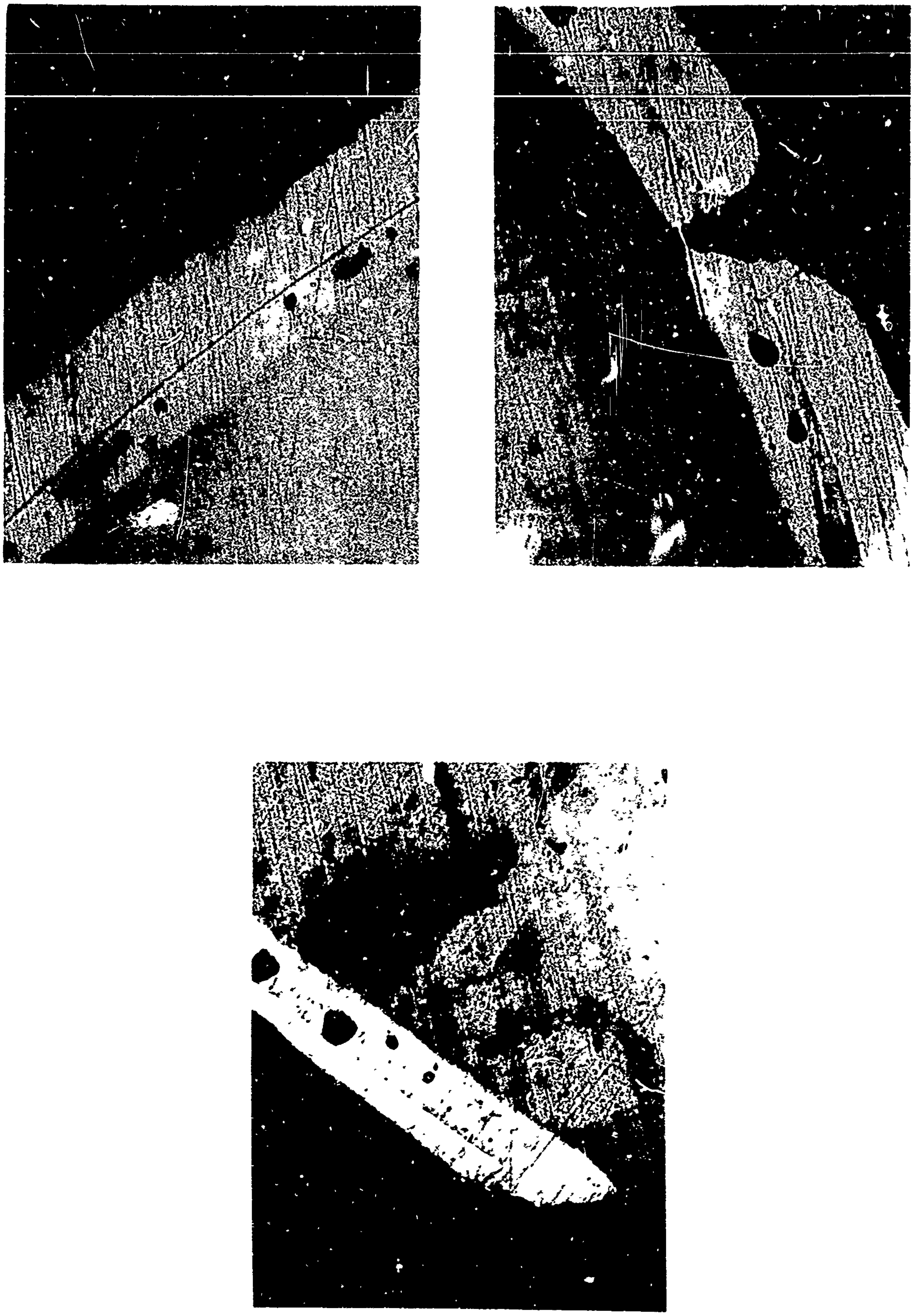
	Anode	Cathode
average temperature increase	39^oC	6^oC
single pulse temperature increase	253^oC	40^oC
maximum surface temperature	315^oC	69^oC

This diode was removed from test after 20 hours of operation because the rf coupler developed a vacuum leak.

6.2.3 Analysis of Vane #20 after Pulsed Electron Bombardment

Vane #20 was removed from diode #4 after it had been subjected to 20 hours of operation and had been bombarded by 14 million pulses. A study of the vane showed severe damage in the region opposite the end shields. Under 27X magnification the whole surface of the vane facing is covered with hills and valleys (reference Figure 6.2). Micrometer measurements indicate that the change in the vane diameter is less than 10^{-4} inches.

There are many dull and bright areas 2 to 4 mm square. In the bright areas, the surface is broken up uniformly and protrusions appear on the surface in waves. In the dull areas, the protrusions are more random.



s.

Figure 6.2 Vane #20

The valleys between the protrusions are in the order of tenths of thousands.

A spectroscopic analysis of the surface of vane #20 indicated the following elements were present:

Element	%
platinum	major
palladium	.1 - 1
copper	.1 - 1
zinc silver nickel iron	.01 - .1
magnesium calcium	.001 - .01
silicon aluminum lead	.0003 - .003
gold	none

The roughening of the surface that has occurred could possibly be due to thermal stresses. Crapuchettes* has developed an expression for thermally induced stresses. This expression is as follows:

$$\frac{S}{\Delta T} = \frac{1.14\, b\, E\, \sigma}{1 - \sigma^2}$$

b	=	thermal expansion coefficient
E	=	modulus of elasticity
S	=	fibre stress
ΔT	=	temperature difference of hot spot from body temperature
σ	=	Poisson's ratio.

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* op cit page 17.

If the assumption is made that Poisson's ratio and Young's modulus do not vary with temperature, then the stresses introduced as a function of temperature can be readily calculated. It is reasonable to make this assumption with respect to Poisson's ratio; however, Young's modulus is probably a strong function of temperature.

A plot of thermally introduced stresses in platinum, as a function of temperature, is given in Figure 6.3. The ultimate tensile strength of platinum as a function of temperature is also given in this figure.

This figure shows that the thermally induced st ess at diode #4's operating level is above the tensile strength of platinum; hence, the surface of the platinum vane facing of vane #20 underwent plastic deformation.

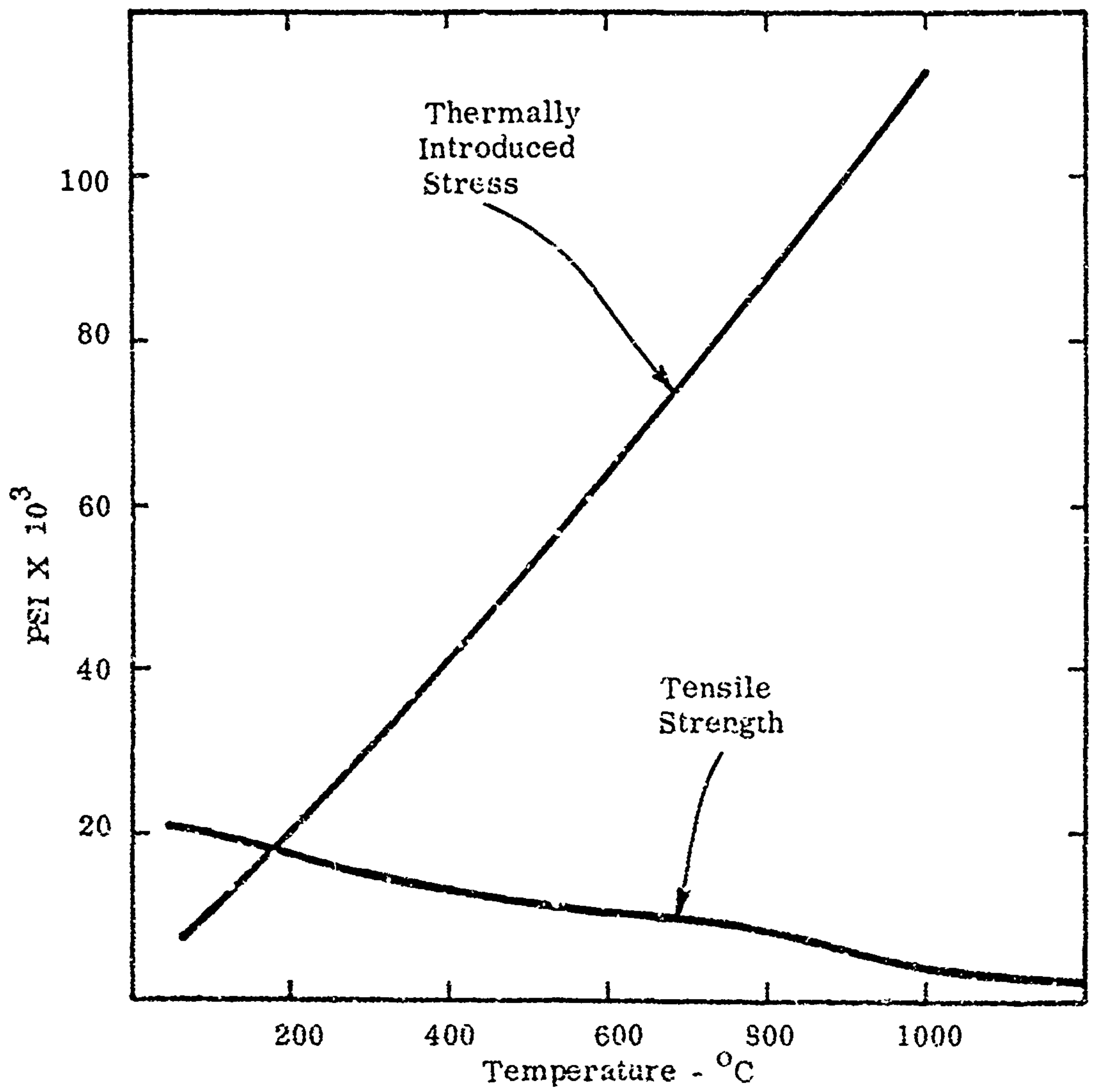
During plastic deformation, slipping or mechanical twining takes place. Slipping and twining cause the formation of microscopic steps on the surface of a metal. These microscopic steps are formed by the projecting ends of the crystal layers which have been displaced with respect to one another.

The presence of these microscopic steps produces an enhancement of the field strength in the neighborhood of the step and increases the likelihood of breakdown. The maximum field strength withou. enhancement is 150 kV/cm.

6.3 Evaluation of Vane #22 from Diode #5

6.3.1 Description of Diode #5 and Vane #22

Diode #5 consists of an inverted magnetron diode with internal poles with an anode-to-cathode ratio 5% larger than the standard diode. The reason for changing the cathode diameter was to increase the maximum power dissipated in the diode. The assumption that this change would increase the total power dissipated in the diode



THERMAL STRESS VERSUS TEMPERATURE

Figure 6.3

results from Jepson and Muller's* study of enhanced emission from pure metal magnetron cathodes. They showed that a gap reduction of 26% (V_a/r_c decreased from 1.99 to 1.58) caused over a 65% increase in the total power dissipated in the diode. The dimensions of this diode are as follows:

anode diameter	.311"
cathode diameter	.486"
total vane length	2.375"
interaction area length	.400"
platinum vane cladding	.005"

This diode was initially tested under the following conditions

pulse width	4 μsec
repetition rate	100 pps
magnetic field	2500 gauss
rf starter signal	80 kW at 3050 Mc.

The initial test data taken on this diode are shown in Figure 6.4. The cutoff voltage for this diode at 2500 gauss is 48 kV. The predominant mode of operation of this diode was between 15 to 18 kV with a current maximum of 17 amperes. On several occasions, the diode operated between 37 and 40 kV; however, operation at the higher voltage was unstable.

6.3.2 Life Test Operation

Diode #5 was life tested under the following conditions:

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* op cit page 8.

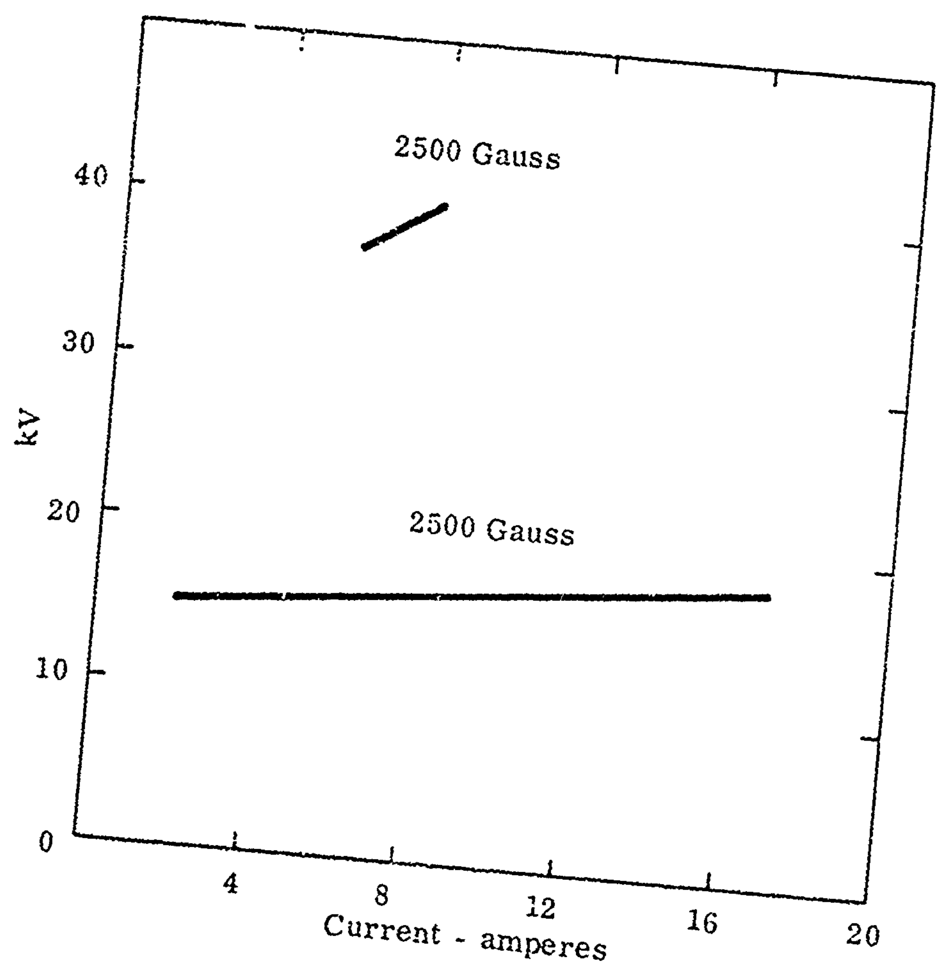

Figure 6.4. E-I Curve for Diode #5.

anode dissipation density	96 kW/cm^2
cathode dissipation density	15 kW/cm^2
pulse width	10 μsec
repetition rate	200 pps
total operating time	20 hours
total number of pulses	12 $\times 10^6$

Operation at the above indicated level produces the following temperature increases:

	Anode	Cathode
average temperature increase	39°C	6°C
single pulse temperature increase	253°C	40°C
maximum surface temperature	315°C	69°C

This diode was removed from test after 17 hours because the rf coupler developed a vacuum leak.

6.3.3 Analysis of Vane #22 after Pulsed Electron Bombardment

Vane #22 was removed from diode #5 after it had been subjected to 17 hours of operation and had been bombarded by 12 million pulses. A study of the vane showed surface cracks on the platinum-clad interaction section of the vane. There are two cracks which extend 80% of the length of the cladding. In several regions, the cracks are melted over. Each crack occurs about 90° from where the two edges of the platinum butt together. Over most of the vane facing, there are small hills and valleys and many small shiny islands 5 to 10 thousandths of an inch on a side. Micrometer measurements indicate that the change in the vane diameter is less than 10^{-4} inches.

Vane #22 was subjected to the same dissipation density and to two million pulses less than vane #20. However, cracking of the platinum facing occurred on vane #22 and not on vane #20. Calculation of the thermal stress to which vane #22 was subjected show that, unless the platinum is undergoing plastic deformation, the thermal stresses introduced exceed the ultimate tensile strength of platinum (reference Figure 6.3).

Orowan's* description of fatigue failure readily explains the difference in the surfaces of vanes #20 and #22. In his picture of fatigue failure, the specimen contains weak spots which act as sources of stress magnification. The weak spots in the two vanes would be random and, hence, would cause a large scatter in the failure points. During the early stages of pulsing, the stress near one or more of the weak spots would rise above the value required for rupture, if the material were not plastic.

However, slip occurs in the region of high stress during the early stages of the pulsing, and, as a result, the stress becomes distributed in such a way that the value for rupture is not exceeded.

Work hardening accompanies the plastic flow so that the strain produced by the stress decreases monotonically during successive pulses. The maximum stress near the weak spot rises with the number of pulses, since it is less effectively distributed by plastic flow. In the region above the endurance limit of the metal, the limiting value of the peak stress is greater than the critical stress for rupture.

Information on the endurance limit of platinum as a function of temperature is not available. However, results on vane #22 indicate that it is discouragingly low.

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*Geitz, F., Physics of Metals, McGraw-Hill Book Company, Inc., New York, 1943.

Melting has occurred at the cracks in the platinum vane facing. The vane has been subjected to a gross field strength of 150 kV/cm. The field enhancement in the region of the crack could be high. Hence, the melting that occurs in the region of the cracks probably results from vacuum breakdown.

The hills and valleys that occur on the surface of vane #22 could be started by the slipping that takes place during plastic deformation. The slipping produces steps on the surface of the metal, which, in turn, cause an enhancement of the field strength. At the average field strength that has been applied to the vane, the surface tensile stress is low. However, the surface tensile stress that is produced is a function of the square of the field strength. With a nominal field enhancement due to surface irregularities, the surface tensile stress may exceed the proportional limit and the surface of the platinum is permanently deformed. At a dissipation level of 96 kW/cm^2, this does not appear to be a major problem.

6.4 Evaluation of Vane #12 from Diode #4A

6.4.1 Description of Diode #4A and Vane #10

Diode #4A is diode #4 rebuilt with vane #10 and a new rf coupler. The dimensions of vane #10 are as follows:

outer diameter	.311"
inner diameter	.125"
total vane length	2.375"
length of interaction area	.400"
platinum vane cladding	.005"

The initial test data taken on this diode are comparable to the data taken on diode #4 shown in Figure 6.1. The permanent magnets used on this tube were gaussed up to 2500 gauss. The cutoff voltage for diode #4A at 2500 gauss is 63 kV.

6.4.2 Life Test Operation

Diode #4A was life tested under the following conditions:

anode dissipation density	123 kW/cm^2
cathode dissipation density	18 kW/cm^2
pulse width	9.5 μsec
repetition rate	200 pps
total operating time	24 hours
total number of pulses	17×10^6

Operation at the above indicated level produces the following temperature gradients:

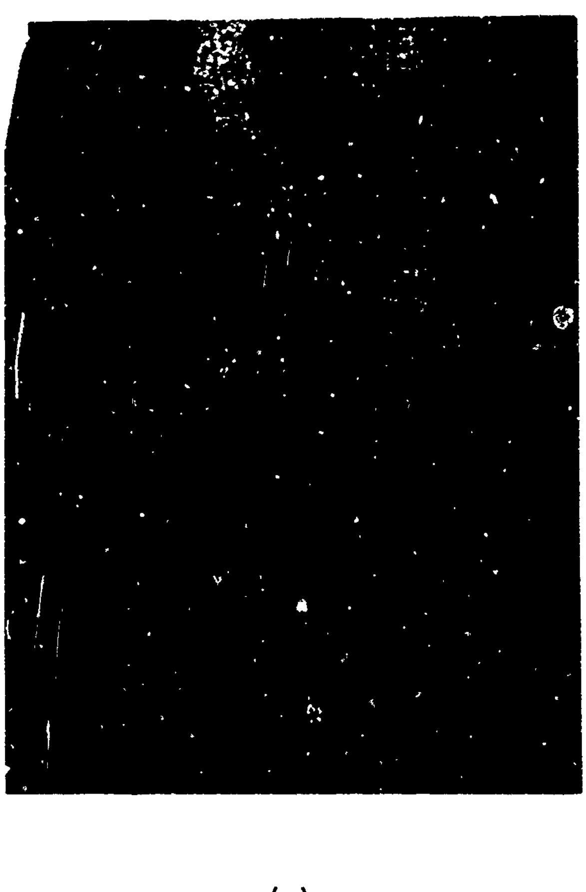
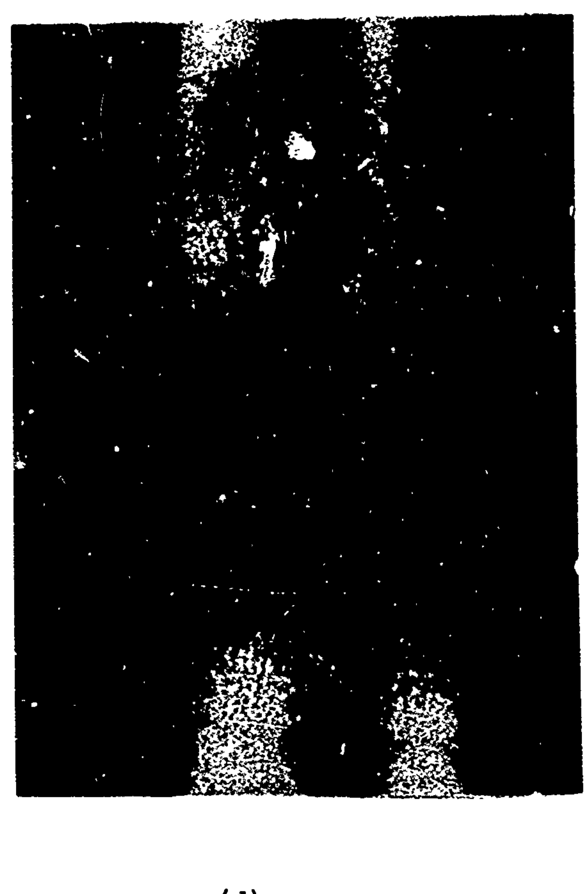
	Anode	Cathode
average temperature increase	50^oC	8^oC
single pulse temperature increase	324^oC	51^oC
maximum surface temperature	397^oC	82^oC

This diode was removed from test after 24 hours of test because the rf coupler developed a vacuum leak.

6.4.3 Analysis of Vane #10 after Pulsed Electron Bombardment

Vane #10 was removed from diode #4 after it had been subjected to 24 hours of operation and had been bombarded by 17×10^6 pulses. Figure 6.5 shows four photographs of this vane after its removal from diode #4A. In section (a) of this figure, many small protrusions approximately .005" in diameter are evident. Poor bonding at the abutting edges of the platinum can be noted, along with concentrated melting in the central region of the cladding and random cracking of the platinum surface. In section (b) of this figure, many pits, 5 to 10 thousandths of an inch in diameter, appear in the platinum surface. There are also many surface cracks which produce little islands 5 to


(a) (b)

(c) (d)

Figure 6. 5 Vane #10 from Diode #4A

10 thousandths of an inch on a side. In section (c) there are signs of uniform cracking of the surface and many small protrusions pulled up from the surface. Here and there, there are small holes of the same size as the protrusions.

In section (d) of Figure 6. 5, uniform surface cracking and many small protrusions can be seen, and an orange peel effect is noticeable. Micrometer measurements indicate that the cha· ·n the vane diameter is less than 10^{-4} inches.

Vane #10 was ..bjected to a peak dissipation density of 123 kW/cm^2. The maximum surface temperature to which the vane was subjected was 397^oC. Figure 6. 3 shows that, at this temperature, the thermally induced stress is 40×10^3 lb/in^2. This value is triple the ultimate tensile strength of platinum at this temperature. Hence, the surface cracking that has occurred is reasonable. The islands formed by the cracks appear to be 5 to 10 thousandths of an inch across. From the analysis of Crapuchettes* this implies a temperature gradient of:

$$\frac{2T}{2X} = \frac{1}{rb} = 2 \text{ to } 4 \times 10^7 \ ^oC/in.$$

However, if we consider the equation for the temperature distribution due to an instantaneous point source in an infinite solid,**

$$T = Q/8 \ (\pi Kt)^{3/2} \ e^{-r^2}/4kt$$

it can be seen that a temperature gradient of $2 \times 10^{5o}C/in$ should exist in the platinum. This large discrepancy in temperature gradient may indicate that the stress cracking is not a one shot effect, whereby the surface cracks and relieves the stress.

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* op cit page 17.

** Proceedings Electron Beam Symposium (March 28-29, 1963)

6.5 Evaluation of Diode #1 and Vane #11

6.5.1 Description of Diode #1 and Vane #11

Diode #1 consists of an inverted magnetron diode, with the standard anode-to-cathode ratio. The dimensions of this diode are as follows:

anode diameter	.315"
cathode diameter	.520"
interaction area length	.400"
platinum vane cladding	.005"

The anode for this diode is vane #11. The vane consists of .300" OD OFHC tubing with a single 1/8" cooling channel. A .005" thick, 0.7" long sheet of platinum is wrapped around the tubing and brazed to it with a gold alloy solder. The cathode for this diode consists of a secondary emitter which is stimulated by an injected rf signal.

The initial E/I curve taken on diode #1 is shown in Figure 6.6. From this curve, it can be seen that the maximum input power to this diode was 690 kW. The cathode dissipated 120 kW of this power and the remainder was dissipated at the anode.

6.5.2 Life Test Operation

Diode #1 was life tested under the following conditions:

anode dissipation density	149 kW/cm^2
cathode dissipation density	23 kW/cm^2
pulse width	9.5 μsec
repetition rate	200 pps
total operating time	110 hours
total number of pulses	79×10^6

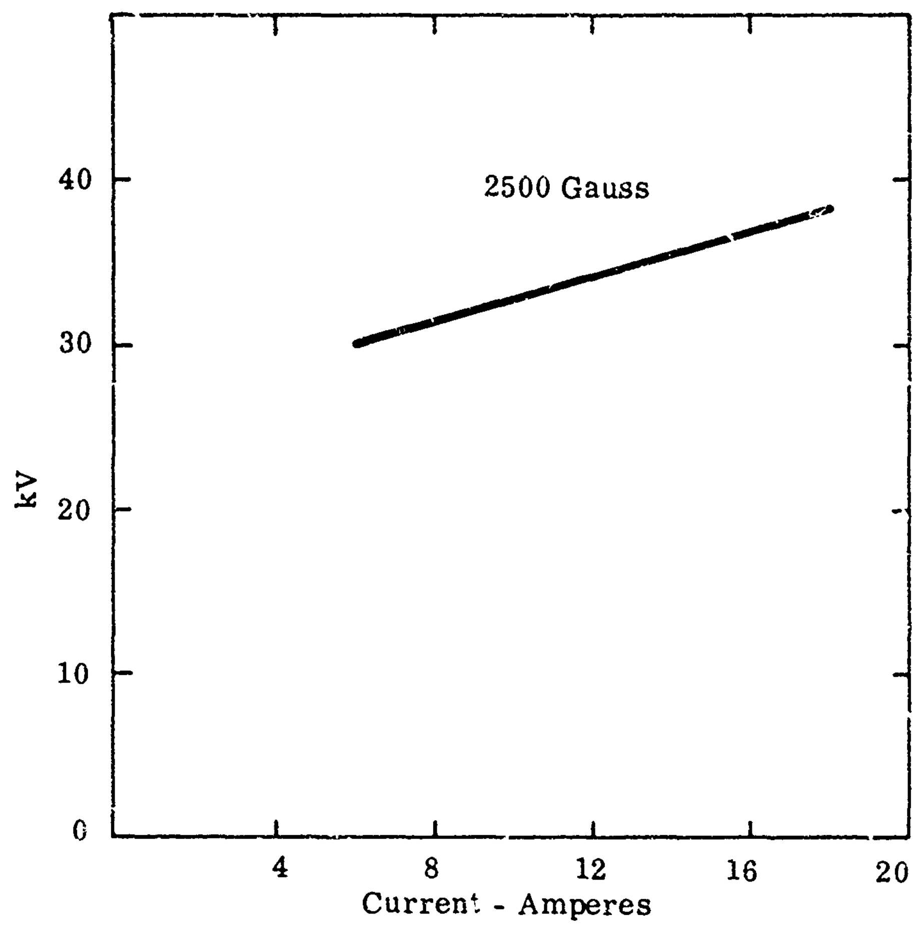


Figure 6. 6. . E/I Curve Diode #1.

Operation at these anode and cathode dissipation densities produced the following temperature gradients:

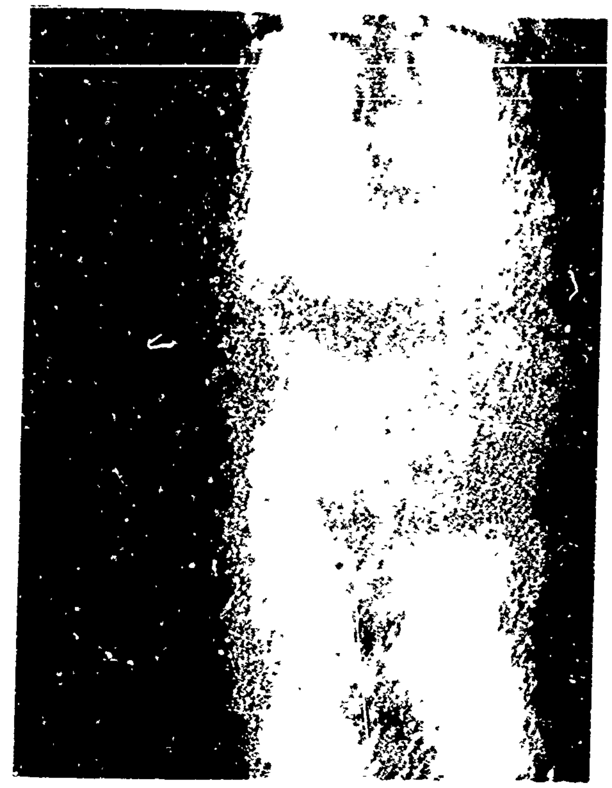
	Anode	Cathode
average temperature increase	$60^{o}C$	$9^{o}C$
single pulse temperature increase	$390^{o}C$	$62^{o}C$
maximum surface temperature	$473^{o}C$	$106^{o}C$

Vane #11 was bombarded at a dissipation level of at least 148 kW/cm^2 for 110 hours. This diode was on the test rack for over 400 hours; however, only 110 hours were at the 148 kW/cm^2 level. The primary reason for this is that it was not possible to drive the diodes with enough rf for simultaneous operation without breakdown in the rf coupler. During the major portion of this operating time, the tube was operated at a repetition rate of 200 pps. However, there were short periods of time when driver instability necessitated operation at PRF's of 300 and 400 pps.

6.5.3 Analysis of the Effects of Pulsed Electron Bombardment on Vane #11

Vane #11 was removed from diode #1 after 110 hours of operation. There were large areas of the diode plated with platinum. These plated areas are located on the outer conductor of the resonant coaxial cavity, and on the unclad ends of the vane. In the interaction region of the vane, the surface has a dull satin finish. There are no gross signs of erosion in this region. Micrometer measurements indicate that the reduction in diameter is less than 1×10^{-4} inches. When the platinum surface is studied under 27X magnification, surface cracks are evident (reference Figure 6.7). There are also low random rows of platinum located in the interaction area. The maximum surface temperature of the platinum vane facing is $473^{o}C$. The thermally induced stress, assuming no plastic deformation, is 49×10^3 lb/in^2 (reference Figure 6.3). This high thermal stress greatly exceeded the ultimate tensile strength of platinum and caused the observed surface cracks. The random rows of platinum located in the interaction area are also caused by the high thermal stress. At these high stress levels, plastic deformation takes place, and hence slipping and twining.

(a)



(b)

(c)

(d)

Figure 6.7 Vane #11 from Diode #1

6.6 Evaluation of Diode #6 and Vane #26

6.6.1 Description of Diode #6 and Vane #26

Diode #6 consisted of an inverted magnetron diode, with internal pole pieces, a platinum cathode and a platinum clad anode. The anode is vane #26. The dimensions of this vane are as follows:

outer diameter	.311"
inner diameter	.125"
length of interaction area	.400"
platinum vane cladding	.005"

Electron emission is obtained from the platinum cathode by exciting secondary electrons with rf.

This diode was initially tested under the following conditions:

pulse width	10 μsec
duty cycle	.001
magnetic field	2500 gauss
rf starter signal	80 kW at 3042 Mc.

The initial test data taken on this diode are shown in Figure 6.8.

6.6.2 Life Test Operation

Diode #6 was life tested under the following conditions:

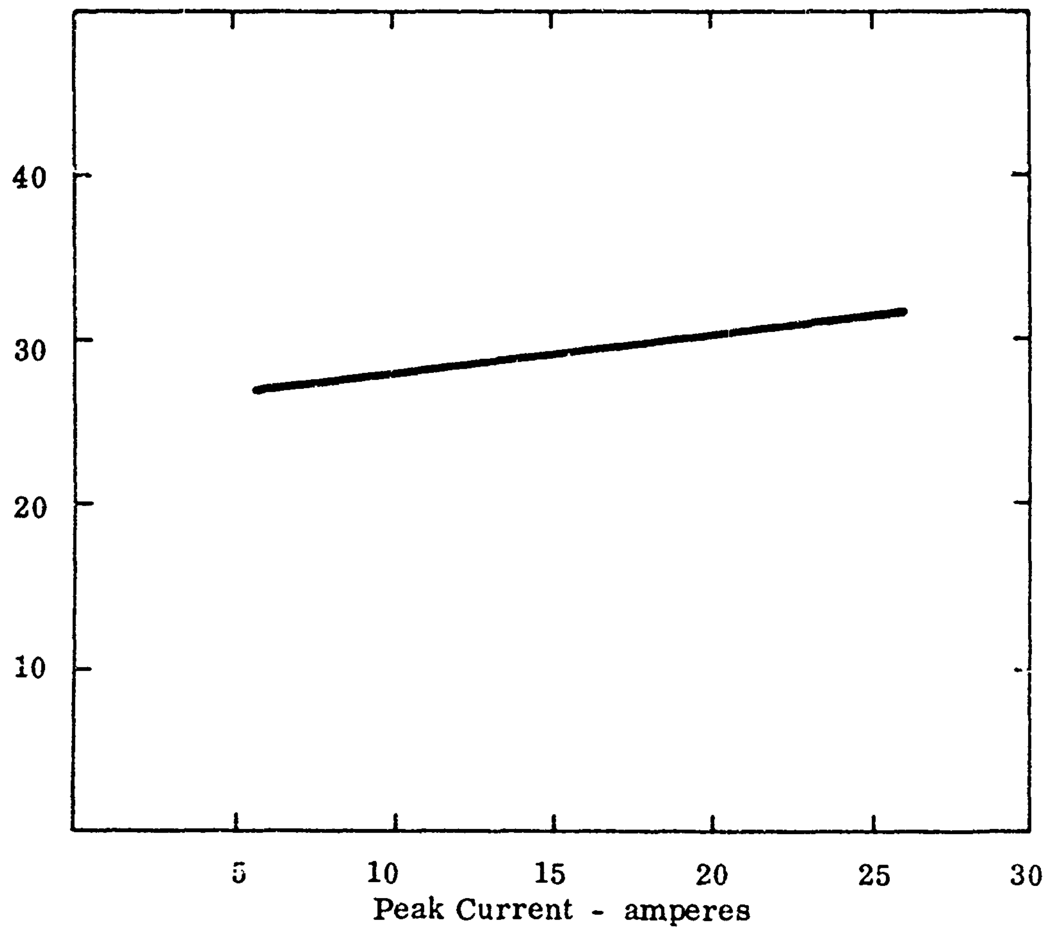


Figure 6.8. E-I Curve for Diode #6.

anode dissipation density	250 kW/cm^2
cathode dissipation density	37 kW/cm^2
pulse width	9.5 μsec
repetition rate	200 pps
total operating time	275 hours
total number of pulses	200 x 10^6

During the major portion of life testing, the PRF was 200 pps. However, there were short periods when operation at 300 and 400 pps was necessary to attain driver stability.

Operation at the above level produces the following temperature gradients:

	Anode	Cathode
average temperature rise	100^{o}C	15^{o}C
single pulse temperature rise	660^{o}C	97^{o}C
maximum surface temperature	783^{o}C	135^{o}C

Reference to Figure 6.3 shows that this anode surface heating produces stresses which are many times the ultimate tensile strength of platinum. Plastic deformation will take place for a number of pulses and will keep these large stresses from being set up. However, as work hardening takes place, the platinum will lose its plasticity and rupture will occur. The fact that platinum can tolerate large plastic deformations at elevated temperatures may indicate that platinum has a low susceptability to thermally induced cyclic stress.

6.6.3 Analysis of the Effects of Pulsed Electron Bombardment on Vane #26

Vane #26 was removed from diode #6. The surface of the vane, which had a high polish at the start of the test, was dull and roughed up at the end of test. (Ref. Figure 6.9.) Micrometer measurements of the vane diameter showed that the change in vane diameter was less than 1 x 10^{-4} inches. Large areas of the anode block were plated with platinum. Figure 6.10 shows that 10^{15} pulses would be required to evaporate one

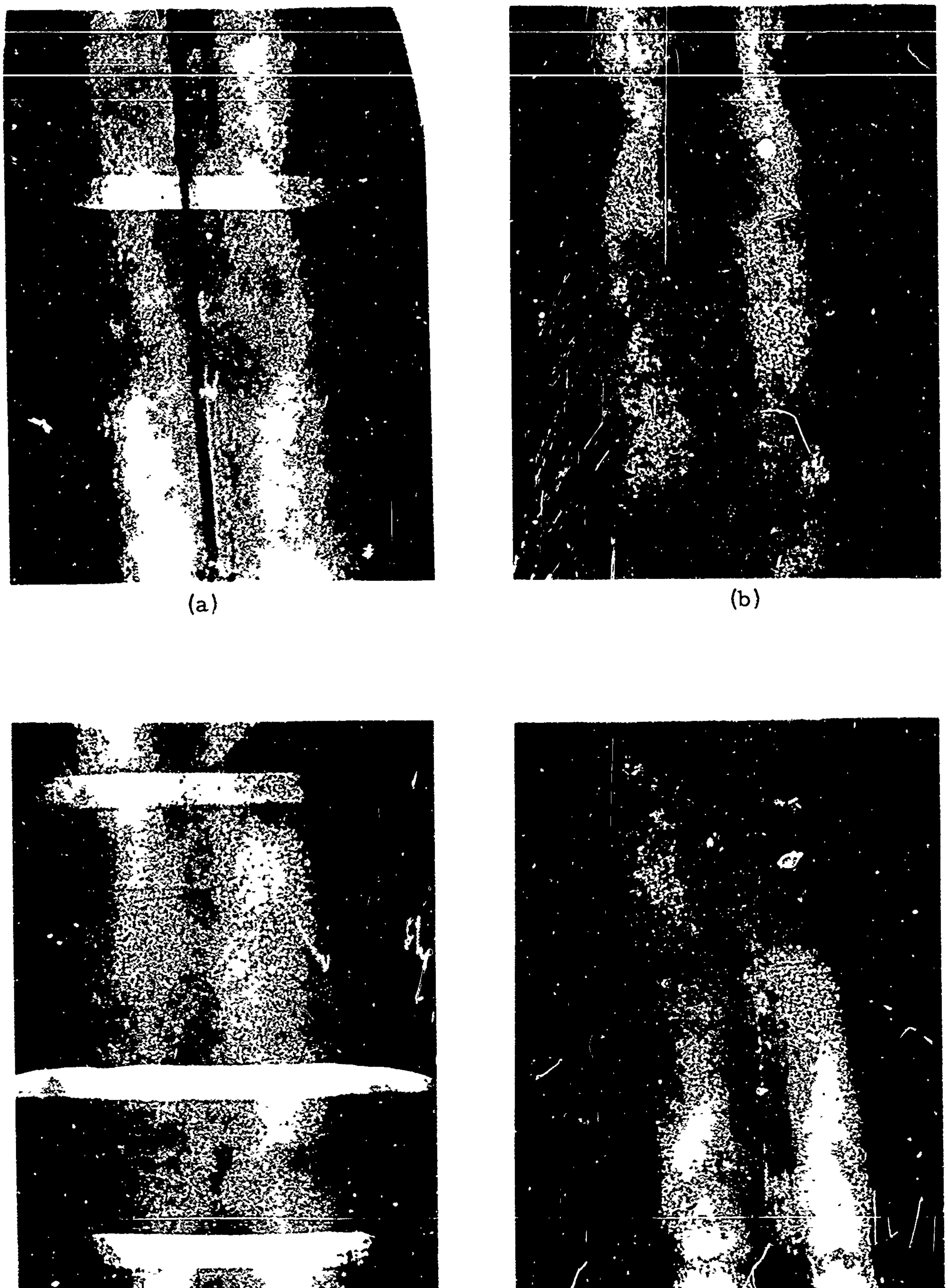


Figure 6.9 Vane #26 from Diode #6

* N = Number of pulses required to desorb .001" of material.

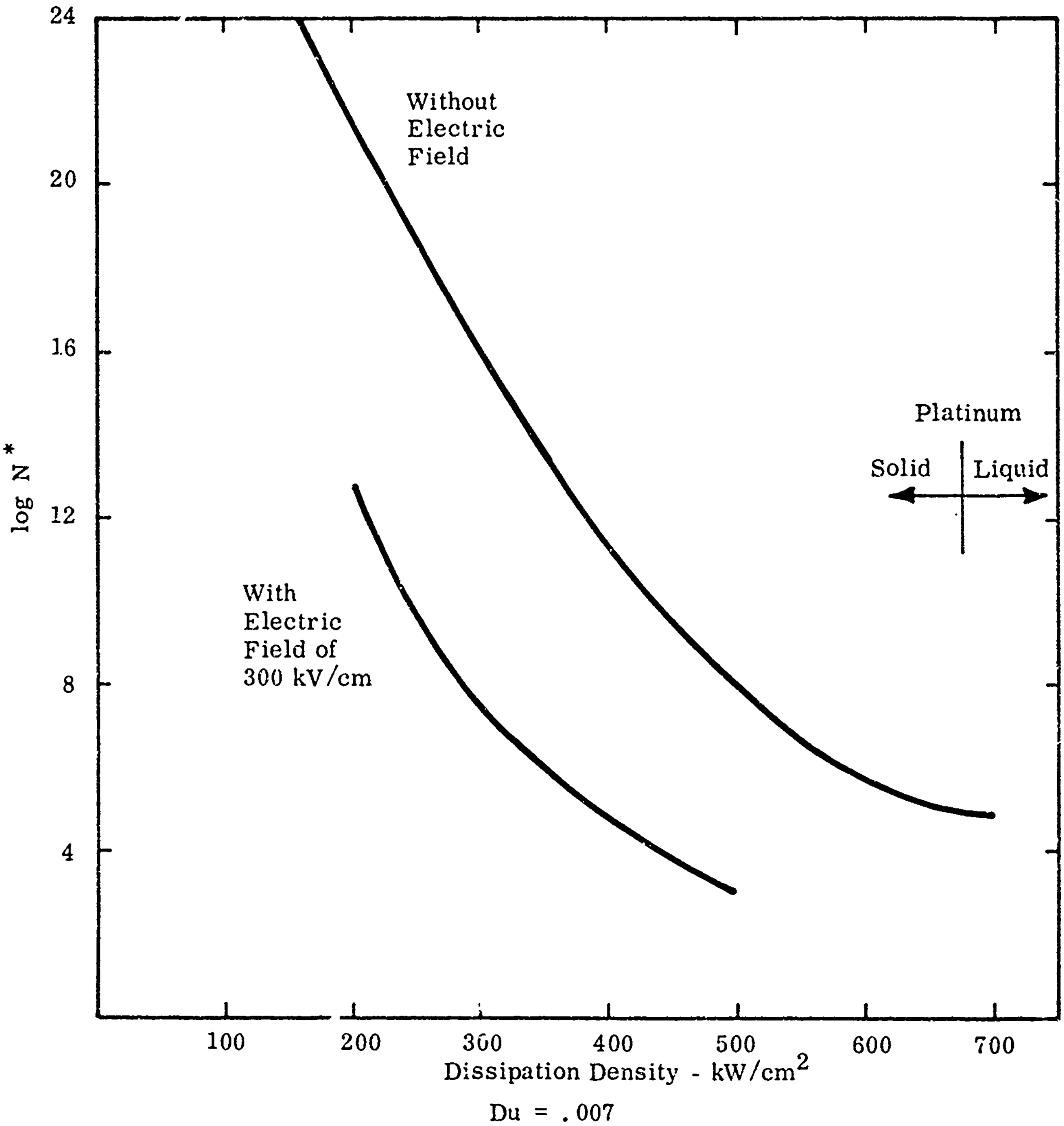


Figure 6.10. Desorption With and Without an Applied Field

atomic layer of platinum from the vane facing. Utilizing the work of E. W. Miller (ref. Appendage 1) on field desorption of a metal from its own lattice, it can be shown that 30 atomic layers of platinum would have been desorbed during the testing of diode #6 (ref. Figure 6. 10).

There were many straight cracks on the surface of vane #26 perpendicular to the axis of the vane. (Reference Figure 6. 9 (d)). These cracks extend almost all the way around the vane and are spaced ten to fifteen thousandths of an inch apart. Also, uniform cracking of the platinum has broken up the surface of the platinum into small islands of approximately ten thousandths of an inch on a side (reference Figure 6. 9 (b) and (c)). This cracking and roughening of the surface is the result of the high thermal stress existing at the vane surface. At surface irregularity sites, large field enhancements will take place. At these sites, the desorption rate of the platinum will be enhanced because of the field enhancement. An example of how much the desorption rate will increase can be seen by considering the desorption rate increase with a field enhancement of 100. With a field enhancement of 100, seventy thousandths of an inch of platinum would be desorbed in the period that this diode was on test. The desorption rate is enhanced by a factor of 230, 000.

The above indicates that the following mechanism can account for the large amount of platinum plated on numerous areas of the diode.

After the anode has been bombarded for a period of time, the high thermal stresses cause surface cracks. At these surface cracks, enhancement of the fields occur. At the sites of high field concentration, rapid desorption takes place. This rapid desorption rate will continue until the sites of high field concentration are eroded away and the high field concentration no longer exists. The rate of desorption will asymptotically decrease to the rate determined by the gross field strength. The assumption that the rate of desorption will decrease is based on the requirement that field enhancement does not continue to occur. After the surface of the platinum has been thermally stressed beyond its endurance limit, surface cracking will take place and thereby relieve the stress. The surface may then become stable and no further cracking will take place. Another mechanism for producing field enhancement is vacuum breakdown. The high rate of desorption that may take place after stress cracking will produce a vapor cloud in the interaction area. If this vapor cloud is dense enough, it will cause vacuum breakdown. This breakdown in turn will produce craters and roughening of the surface, and, hence, field enhancement.

The rate of surface diffusion produced by the gross fields in the diode is negligible. However, at the enhanced field sites produced by the above mechanisms, the surface diffusion rate may be great enough to grow projections or high field sites at a more rapid rate than they are desorbed or destroyed by vacuum breakdown. If this was so, a very high rate of erosion would occur continuously.

Vane #26 showed noticeable effects due to the above indicated mechanisms. However, these effects are such that thousands of hours of operation should be possible at 250 kW/cm^2.

6.7 Evaluation of Diode #3 and Vane #18

6.7.1 Description of Diode #3 and Vane #18

Diode #3, with vane #18, on the anode is an inverted magnetron diode. The cathode consists of a water-cooled platinum surface of .520" diameter and .400" length. Vane #18 is a .300" OD, .125" ID copper tubing. The outer surface of the anode is clad with .005" platinum.

In order to start the secondary emission from the platinum cathode, a drive signal of 3050 Mc is coupled into the diode through a 7/8" coaxial line terminated in a loop. The diode forms a coaxial cavity which resonates at 3050 Mc.

This diode was initially tested under the following conditions:

pulse width	10 μsec
repetition rate	100 pps
magnetic field	2500 gauss
rf starter signal	138 kW (3042 Mc)

During initial tests, the diode operated up to 1.2 mw of peak power dissipation in the anode and 215 kW in the cathode with an anode voltage of 38.5 kV. An E/I curve taken on this diode is shown in Figure 3.5. The cutoff voltage for this diode at the 2500 gauss level is 63 kV. In this voltage region, diode #3 will not draw current.

6.7.2 Life Test Operation

Diode #3 was operated on life test for a total of 330 hours, at a 9.5 μsec pulse width. During this period, the diode was pulsed 240 million times. The following indicates the peak anode and cathode dissipation during life test of this diode.

	Anode	Cathode
total dissipation	700 kW	154 kW
dissipation density	280 kW/cm^2	37 kW/cm^2

This diode was operated for a period of 20 hours at an anode dissipation density of 400 kW/cm^2 when the diode was run on a separate test set. However, on the life test rack it was not possible to attain sufficient drive to operate at this level, hence the dissipation level of 280 kW/cm^2 was chosen for life testing.

The above dissipation densities produce the following temperature gradients:

	Anode	Cathode
average temperature rise	112°C	16°C
single pulse temperature rise	740°C	97°C
maximum surface temperature	875°C	136°C

Reference to Figure 6.3 shows that this amount of surface heating of the anode will produce stress cracking.

6.7.3 Vane Analysis After Pulsed Electron Bombardment

Vane #18 was removed from diode #3. The surface of the vane, which had a high polish at the start of the test, was dull and roughed up at the end of the test. Micrometer measurements of the vane diameter indicate an increase in diameter of several thousandths. Microscopic examination of the surface of the metal shows the surface to be covered with what appears to be many small beads (ref. Figure 6.11) of approximately .005" diameter. There are areas where many waves of projections exist.

This vane shows numerous protrusions rising above the surface. The tips of many of the projections are melted or eroded away and rounded off, hence giving the appearance of small beads. The applied fields, under the conditions to which this diode was subjected, have been great enough to overcome the surface tension and allow surface diffusion to take place. Calculation of the stress set up in the surface of the vane at field strengths of 150 kV/cm show that the stress would be 10,000 dynes/cm^2. At a temperature of 2000°C, the surface tension of platinum is such that surface diffusion will readily take place with the above applied fields. The surface tension of platinum at the operating temperature (875°C) is not known. However, the above indicates that it is less than 4000 dynes/cm.

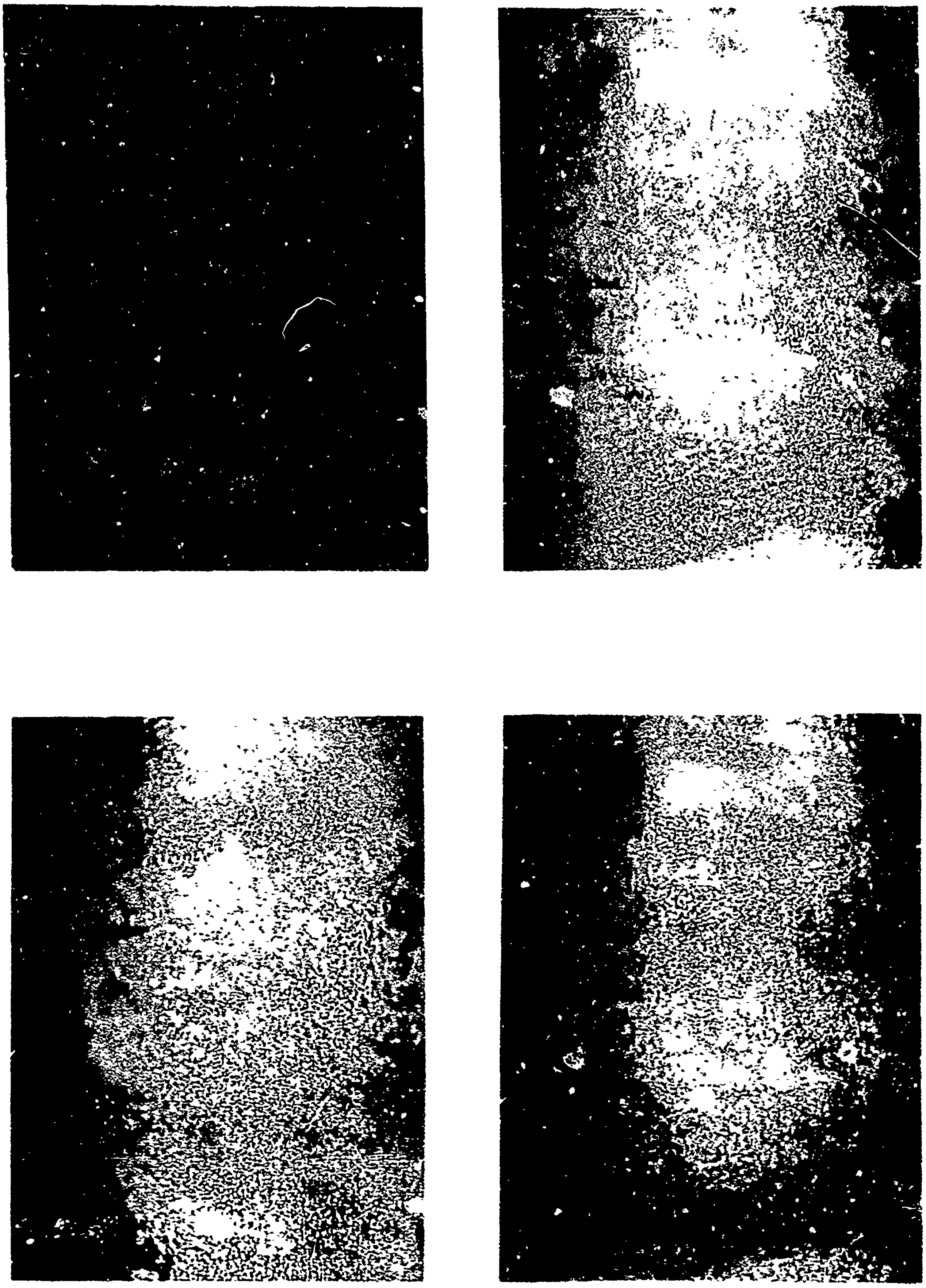


Figure 6.11 Diode #3 Vane #18

7.0 CONCLUSIONS

During this program, the test vehicle and facility required to carry out a statistically meaningful evaluation of materials useful for peak power Amplitron vanes have been developed. The test vehicles and facility have been evaluated and shown to give meaningful results in the case of platinum. Platinum was evaluated because it is the vane facing used in the super power pulsed Amplitron.

This program should be continued so that the other five promising materials studied, and reported in Section 4.0, are evaluated with respect to the effects of pulsed electron bombardment as a function of dissipation density and time. These materials all have specific advantages over platinum. Because of this, the evaluation of these materials in a program similar to that used to evaluate platinum could substantially improve the peak power capability of Amplitron vanes.

8.0 FACILITY MAINTENANCE

Contract AF30(602)-3441 also provided for the maintenance of the Super Power Test Facility and the electrical power demand and energy used. The test facility consists of two 40 kilovolt, 55 ampere power supplies, a 70 megawatt, 500 kilowatt average hard tube modulator, four test bays, low pressure and high pressure pure water cooling systems, main control room, rf driver chain, and special test and exhaust equipment.

Maintenance of the Super Power Test Facility consisted of routine preventive maintenance as well as the repair of equipment failures during the performance of life tests of the QR849, QR871 Amplitrons and the special pulsed diode. Routine maintenance consisted of work such as periodic testing of small tubes and components and replacement when necessary, inspection and calibration of electronic and hydraulic instruments and components, lubrication, changing of filters, dessicants, demineralizer resins, and other expendable materials.

Major repairs consisted of the replacement of a QK622 driver Amplitron and the rebuilding of another, repair of a CSH9 circulator and repair of the damage caused by the failure of a "pot head" at the output of a three phase rectifier transformer.

Maintenance work was performed by a full-time electronic specialist, an electronic technician and as required by other maintenance personnel such as plumbers, carpenters, electricians, mechanics, machinists, painters, and millwrights.

The cost of electrical power was borne by this contract. Power consumption by the test facility was measured by watt-hour meters with recorders located in the facility switch gear enclosure. Cost was based on peak demand as well as total power consumption during each billing period.

APPENDIX I

FIELD DESORPTION OF A METAL FROM ITS OWN LATTICE

APPENDIX I

FIELD DESORPTION OF A METAL FROM ITS OWN LATTICE

The amount of metal desorbed from its own lattice in the presence of a high electric field is indicated in the work of E.W. Muller.* He indicates that the field strength required to desorb one atomic layer of a metal from its own lattice is given by

$$F = \frac{1}{(ne)^3}\left(q_o - kT\ln\frac{\tau}{\tau_o}\right)^2 \frac{1}{C^2}$$

q_o	=	binding energy = ev
n	=	effective charge of atom being desorbed $\simeq$ 1.26
e	=	4.8×10^{-10} esu
T	=	temperature in ^oK
τ_o	=	vibration time of ion = 10^{-13} sec
τ	=	operating time
c	=	3×10^{10} cm/sec
F	=	field strength - volts/cm

For platinum and tungsten the above expression reduces to:

$$F = A - BT - CT \log \tau$$

			Pt.	W
where:	A	=	19×10^6	53.7×10^6
	B	=	18×10^3	18×10^3
	C	=	10^3	10^3

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* E.W. Muller, "Field Desorption," Physical Review, Vol. 102, #3, pg. 618.

Plots of this expression for platinum and tungsten in families of curves with temperature as the parameter show that the field strength required for desorbing a metal from its own lattice varies drastically with time and temperature. (Reference Figure 1.)

The time required to desorb 1×10^{-3} inches of platinum or tungsten as a function of temperature and at a field strength of 300 kV/cm is expressed by the following formulas:

$$\tau_W = 10^{\frac{53.4 \times 10^3}{T} - 13}$$

$$\tau_{Pt} = 10^{\frac{18.7 \times 10^3}{T} - 13}$$

These expressions (ref. Figure 2) can be used to determine the life expectance of particular platinum or tungsten vane facings.

F - mV/cm

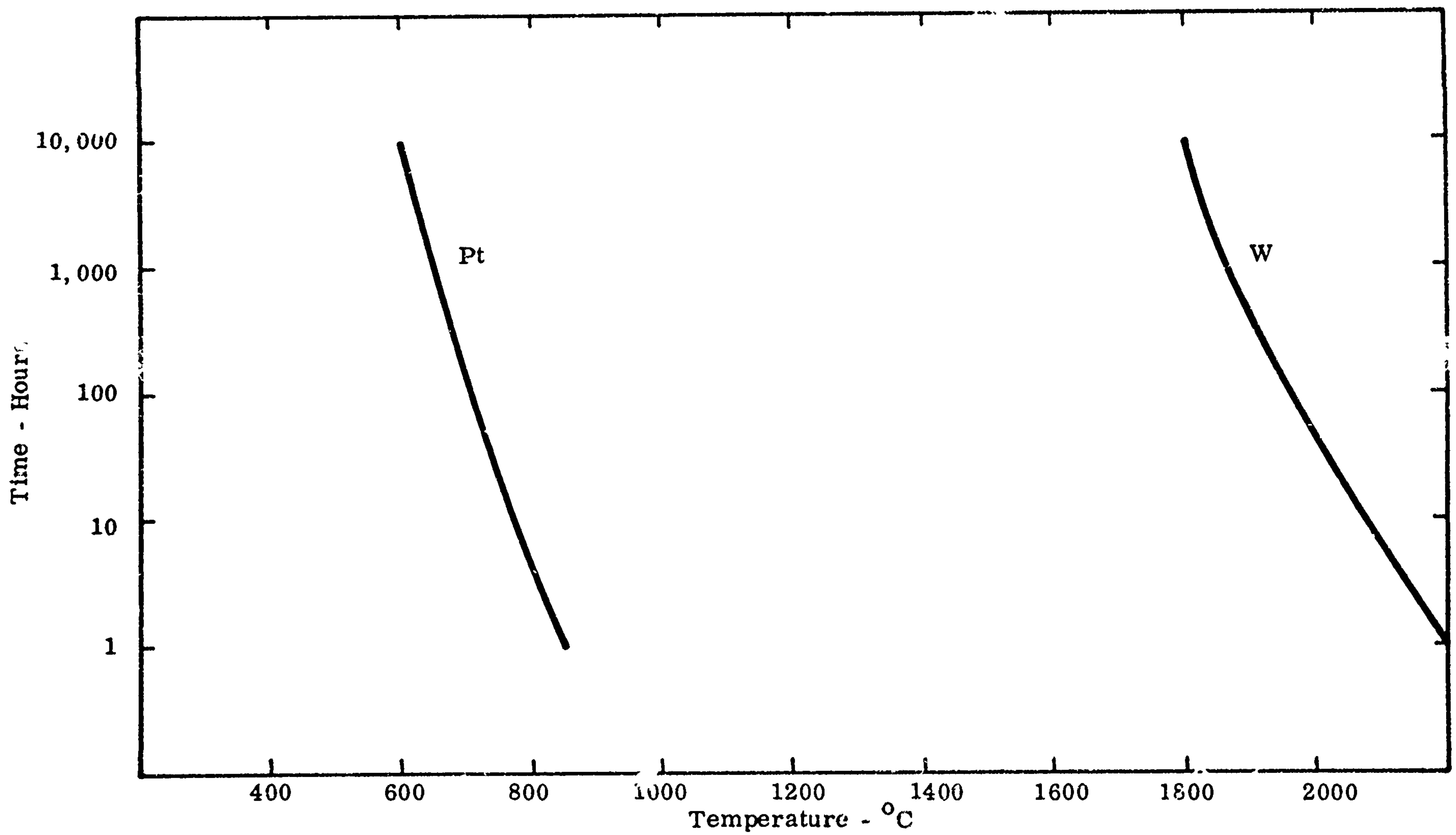

Figure 2. Time Required to Desorb .001" of Metal as a Function of Temperature At a Field of 300 kV/cm.

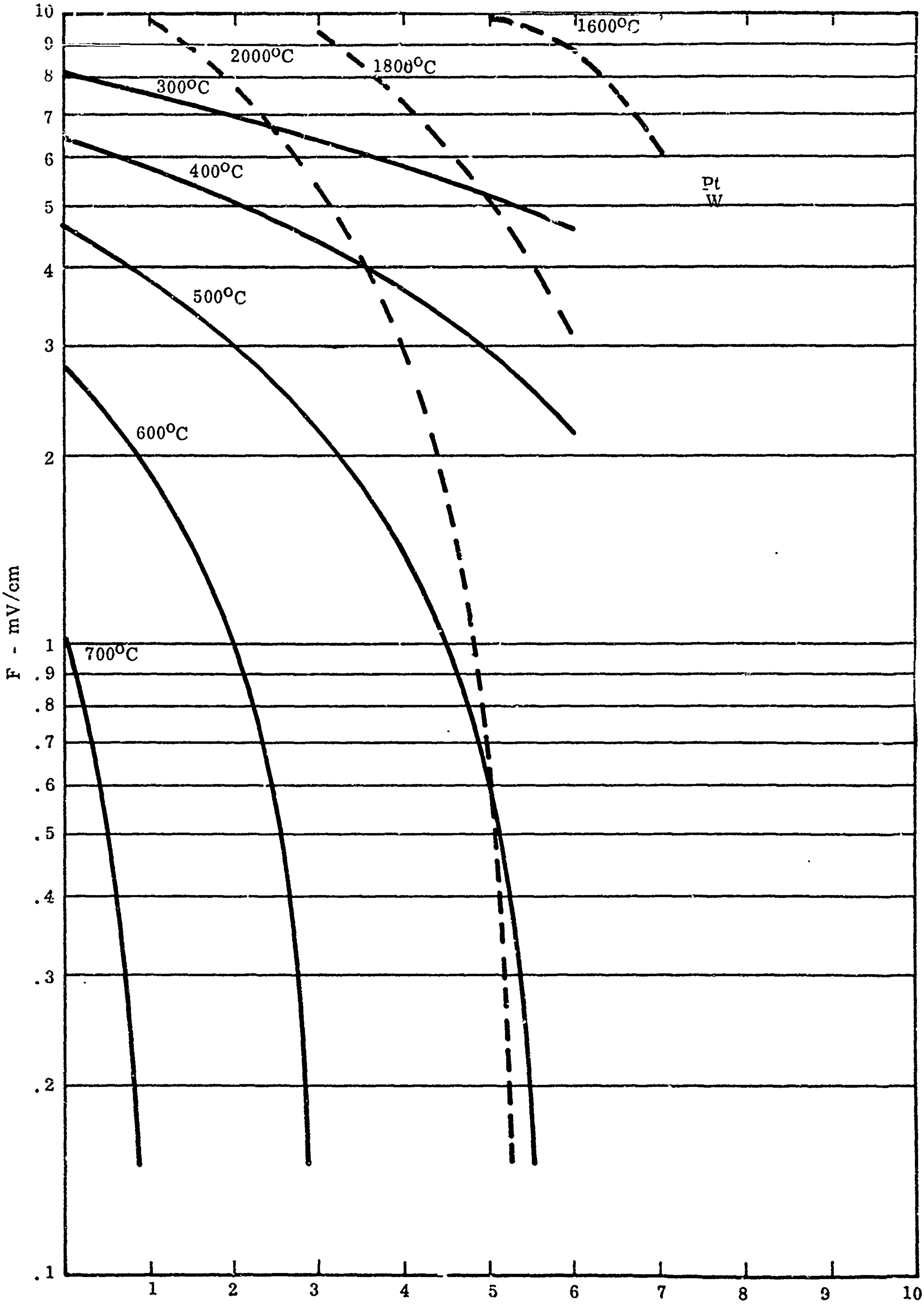

Figure 1. N = log τ τ = time (sec)